Economic Assessment and Comparison of Alternative Beta Alumina Electrolytes

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Prepared by
Compagnie Générale D'Electricité
Marcoussis, France

ELECTRIC POWER RESEARCH INSTITUTE

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Research Project 109-6

Final Report, April 1981
Work Period: January–December 1979

Prepared by

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Prepared by
Compagnie Générale D'Electricité
Marcoussis, France

ABSTRACT

This project had the broad objectives of assessing the costs of β- and β"-alumina, and of comparing the cost of a 100-MWh battery using a β"-alumina electrolyte with the cost of a similar battery using β-alumina.

The production cost of 8,000,000 β- and β"-alumina tubes (inside diameter, 25 mm ; length, 375 mm ; wall thickness, 1.5 mm) was determined for different production routes, first using proved laboratory procedures, and then using an extrapolation of the laboratory processes. The calculated selling price for 100 tubes (1980 U.S. $) ranges from $717 to $1,274 using proved laboratory procedures, and from $649 to $885 using an extrapolation of those procedures. Cost of quality control is included.

Costs were calculated for β"-alumina tubes with 47 cm^2 to 599 cm^2 of active area manufactured via different routes ; tubes with active areas ranging from 200 to 400 cm^2 had the lowest calculated selling price ($2.6 per 100 cm^2).

Based on a production of 25 units a year, the cost estimate for a 100-MWh battery made with a β-alumina optimized cells is $90.3 per kWh. Shifting from β- to β"-alumina, without optimization of the unit cell, results in a cost of $88.9 per kWh, a decrease of 2 %. Assuming equal reliability for β- and β"-alumina, a shift from β- to β"-alumina along with optimization of the unit cell (523 Wh) results in a decrease of 8 % in the total cost to $83.7 per kWh. Moreover, the use of β"-alumina appears more attractive than the use of β-alumina : the production process can be simplified, related cathode requirements are less stringent, and prospects for future improvements are greater.

EPRI PERSPECTIVE

PROJECT DESCRIPTION

This project, RP109-6, analyzes the manufacturing costs of two types of ceramic electrolytes used in the sodium-sulfur battery. The analysis assumed fabrication procedures demonstrated in the laboratory and separately assumed advanced production processes yet to be proven.

PROJECT OBJECTIVES

The major objective was to estimate the cost of the electrolytes used for sodium-sulfur batteries. Additional objectives were:

1. To identify areas where cost reduction is possible
2. To quantify the potential for cost reduction
3. To economically optimize electrolyte size
4. To compare the cost of the two common forms of electrolytes (β and β'')
5. To compare costs of two sintering techniques

PROJECT RESULTS

The study shows that the electrolytes are very high-cost elements of the sodium-sulfur battery. The estimated price for each electrolyte is about $23/kWh when manufactured by the most cost-effective route. This estimate is about a factor of 10 higher than the envelope calculations made a few years back. However, the projected price is substantiated by the considerable detail presented herein, the involvement of an established ceramic manufacturer (Ceraver) in this study, and price comparisons with similar commercial ceramics. The price of $23/kWh for each electrolyte is about one-third of the cost goal for the battery. This price assumes that saggers (containers used in the sintering step) are eliminated or have lifetimes considerably longer than those demonstrated in the laboratory. In one case, elimination of saggers resulted in a materials cost reduction of 84% and a factory cost reduction of 40%. Since the elimination of the saggers presents by far the greatest single opportunity for cost reduction, research and development to accomplish this goal is in order.

A potentially important conclusion of this study is that substantially higher costs are projected for pass-through sintering than for batch sintering. This result suggests that the presently preferred sintering approach of many of the world's sodium-sulfur battery developers is not the economically preferred approach.

A surprising and disappointing result of this study is that electrolyte tube price does not seem to be lowered much by manufacturing automation. Lower labor costs were more than offset by the higher depreciation, ROI, and taxes associated with the relatively expensive manufacturing equipment assumed in the study. Clearly there is an opportunity for innovation in electrolyte manufacturing, but it is too early to project how far the ultimate economic benefit of new manufacturing concepts will extend.

James R. Birk, Project Manager
Energy Management and Utilization Division

FOREWORD

This report describes the work performed between January 1, 1979, and December 31, 1979, for Electric Power Research Institute Project RP109-6, "Economic Assessment and Comparison of Alternative β-Alumina Electrolytes."

It is divided into four parts :

Part A : Cost Evaluation for β-Alumina Electrolytes

Part B : Cost Evaluation for β"-Alumina

Part C : Comparison

Part D : Quality Control Procedures

Parts A, B, and D were carried out at the Materials Division of the Laboratoires de Marcoussis, with the collaboration of Ceraver ; Part C was carried out at the Electrochemistry Division.

R. L. Vic, Director of the Electrochemistry Division, had management responsibility for the program and Dr. J. R. Birk of the Electric Power Research Institute was Project Manager. Principal Investigators during the reporting period were :

A. Wicker and G. Desplanches (parts A, B, D)

J. P. Pompon and J. Jacquelin (part C)

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Part A : COST EVALUATION FOR β-ALUMINA ELECTROLYTE

Part B : COST ESTIMATE FOR β"-ALUMINA

Part C : COMPARISON

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SUMMARY

This study consisted of four parts :

A. Cost evaluation for β-alumina electrolytes

B. Cost evaluation for β"-alumina electrolytes

C. Comparison

D. Quality control procedures

Part A

In part A, the cost for the production of 8,000,000 β- and β"-alumina electrolyte tubes (inside diameter 25 mm, length 375 mm, and wall thickness 1.5 mm) was assessed for the following manufacturing procedures :

1. Project laboratory processes

   --Powder synthesis by alternative solid state reactions (ref. H11 for spray-dried powder or H12 for electrically charged powder) for β- and β"-alumina

   --Forming by isostatic pressing (ref. J1) for β- and β"-alumina and by electrophoretic deposition followed by isostatic pressing (ref. K1) for β-alumina only

   --Batch sintering with protective saggers (ref. M1) for β- and β"-alumina and pass-through sintering (ref. L1) for β-alumina only

2. Extrapolation of the laboratory processes for β-alumina only

   -- Powder synthesis by alternative continuous solid state reaction (ref. H21 or H22)

--Forming by isostatic pressing at a higher production rate (ref. J2) or by electrophoretic deposition without isostatic pressing (ref. K2)

--Batch sintering with protective sagger of longer lifetime (ref. M2) or with improved pass-through sintering (ref. L2).

The cost of the raw materials, the labor needed for each main step (powder fabrication, forming, sintering, and quality control), the equipment cost, and the production area needed were assessed for the different routes studied. The selling prices of the tubes were then estimated according to the Arthur D. Little guidelines (EPRI Interim Report 1198-2, September 1979). Prices for 100 tubes, in 1980 U.S.$ (production yield 0.75) are :

Laboratory Processes					Extrapolations of the Laboratory Process				
H11	J1	M1	(β)	\$ 717			--		
H11	J1	M1	(β")	\$ 775			--		
H11	J1	L1	(β)	\$1,231	H21	J2	L2	(β)	\$ 885
H12	K1	M1	(β)	\$ 759	H22	K2	M2	(β)	\$ 649
H12	K1	L1	(β)	\$1,274					

The envisioned extrapolation of the laboratory process results in a reduction of 28 % in the selling price of tubes fabricated via isostatic pressing and pass-through sintering, and a reduction of 14 % in the cost of tubes fabricated via electrophoresis with batch sintering.

Part B

In part B, the production cost of β"-alumina electrolyte tubes was assessed for tubes of 5 different sizes (active areas ranging from 47 cm^2 to 599 cm^2) and for 4 different manufacturing routes, with the same method as used in EPRI RP726-1. The production routes studied are the same in Part A, case 1.

The lowest costs, approximately \$2.6 per 100 cm^2 of active area, were obtained by using batch sintering for tubes with an active area of 200 cm^2 to 400 cm^2.

Part C

In part C, the cost was estimated for three types of 100-MWh batteries :

- Battery made with β-alumina optimized cells.
- Battery made of cells sized identical to the preceding ones, but made with β"-alumina.
- Battery made with β"-alumina optimized cells.

The total cost for the 100- kWh unit made with β-alumina optimized cells is $90.3 per kWh. Substituting β"-alumina for β-alumina,without further optimization reduces the cost by only 2 % to $88.9 per kWh. Thus in the case of β"-alumina, it is necessary to change the cell dimensions and make use of a thicker electrode working within a smaller capacity range (50 % of theoretical) in a larger cell. The optimal value of useful energy is 523 Wh per cell. In that case, the cost will be $83.7 per kWh. So, shifting from β- to β"-alumina and optimizing cell size for the β"-alumina permits an 8 % reduction in the total cost of the unit. This result implies an equal reliability for both β- and β"-alumina cells. From a technical point of view, β"-alumina is definitely more attractive than β-alumina : β"-alumina indirectly permits several simplifications in the system design, cathode requirements are less stringent, and prospects of future improvements are greater.

Part D

In part D, the quality control procedures are defined for the raw materials and for the product after each manufacturing step. Each sintered tube is checked for leak tightness, appearance, geometrical characteristics, and burst strength. The cost of these operations is included in the factory cost. Other characteristics, such as crystalline structure and microstructure, are statistically controlled. The cost resulting from these operations is included in the overhead.

Part A

COST EVALUATION FOR BETA-ALUMINA ELECTROLYTES

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COST EVALUATION FOR BETA-ALUMINA ELECTROLYTES*

A - 1 BACKGROUND

The β- and β"-alumina tubes evaluated in this study are required to have the following dimensions once fired :

- inside diameter 25 mm
- length 375 mm
- wall thickness 1.5 mm

These specifications correspond to an active area of 330 cm^2. Their theoretical weight, calculated from 3.26 density, is 152.4 g. A cell containing this size tube would deliver approximately 280 Wh of energy. Taking into account the trimming required at various stages of fabrication as well as weight loss during sintering, each tube theoretically requires 160 g of raw material. In the hypothetical case of 100 % overall product yield, the required output of 8,000,000 tubes per year would require daily output of 36,364 tubes for 220 working days per year. The quantities of raw materials theoretically required at this production rate are given in Table A-1.

The following procedure was used to determine the factory cost and the selling price :

1. Select a fabrication route

2. Determine the equipment required for that route

3. Evaluate the number of workers needed to maintain the given production rate, at a given number of shifts per day

---

*All cost estimates are given in 1980 U.S. dollars

4. Estimate the labor required to produce 100 tubes at a theoretical product yield of 100 %

5. Estimate the number of machines required for the total production assuming a product yield of 100 %

Table A-1

Theoretically Required Quantities of Raw Materials

βAl_2O_3		$\beta'' Al_2O_3$		
Al_2O_3	5,288 kg	Al_2O_3	5,280 kg	Daily
Na_2CO_3	920 kg	Na_2CO_3	872 kg	
		Li_2CO_3	104 kg	
Al_2O_3	1,164 t	Al_2O_3	1,162 t	Yearly
Na_2CO_3	203 t	Na_2CO_3	192 t	
		Li_2CO_3	23 t	

These steps were conducted with the help of Ceraver, the ceramic manufacturing arm of Compagnie Generale d'Electricite (CGE). Factory cost and selling price were then determined using the guidelines suggested by Arthur D. Little. The main features of the guidelines are listed below.

Production rate

--8 million tubes per year, corresponding to approximately 25 sodium-sulfur battery energy storage systems

Operating schedule

--Two shifts for powder preparation and quality control

--Three shifts for forming and sintering which are capital-intensive processes.

Product yield

--75 % yield factor applied to the production of β-alumina electrolyte tubes. No allowance made for the labor content of the lost materials and components.

Labor cost

--A single labor cost of $10/hour for direct labor. Includes materials handling, shipping and receiving, and quality control.

Overhead rates

--150 % on direct labor and 10 % on purchased materials and components to cover fringe benefits, supervision, and general administrative expense.

Rent

--A standard rate of $5/square foot. (Inclusion of rent as a direct cost avoids the uncertainties associated with real estate values and depreciation schedules.)

Equipment costs and depreciation schedule

--A 25 % mark-up added to the cost of equipment to allow for the cost of its installation. Total amortized linearly over a 10-year period.

Working capital requirements

--Assumed to equal 30 % of the value of annual production taken at factory cost.

After-tax return on investment

--Taken to be a constant annual amount equal to 15 % of the initial invested capital (equipment investment plus working capital). Because depreciation will gradually reduce invested capital, the effective rate of return will increase over the 10-year life of the plant.

Taxes

--The consolidated total of federal, state, and local taxes paid is to equal the after-tax return on investment.

The capital cost of the tubes consists of :

- Factory cost : labor, materials and purchased components, energy (if appropriate), overhead, equipment depreciation, rent
- After-tax return on investment (equipment plus working capital)
- Taxes
- Marketing, warranty, and miscellaneous costs

The main production steps studied are given in Figure A-1. Each step or method is referred to by a letter. In order to prevent confusion, these are different from those used in RP726-1, though there are important similarities. The letter is followed by the figure 1 (for processes directly resulting from laboratory procedures) or 2 (for processes extrapolated from laboratory procedures). (For a full discussion of the letter code, refer to the summary at the front of this volume.)

The calculation results are presented in the sections referred to in figure A-2.

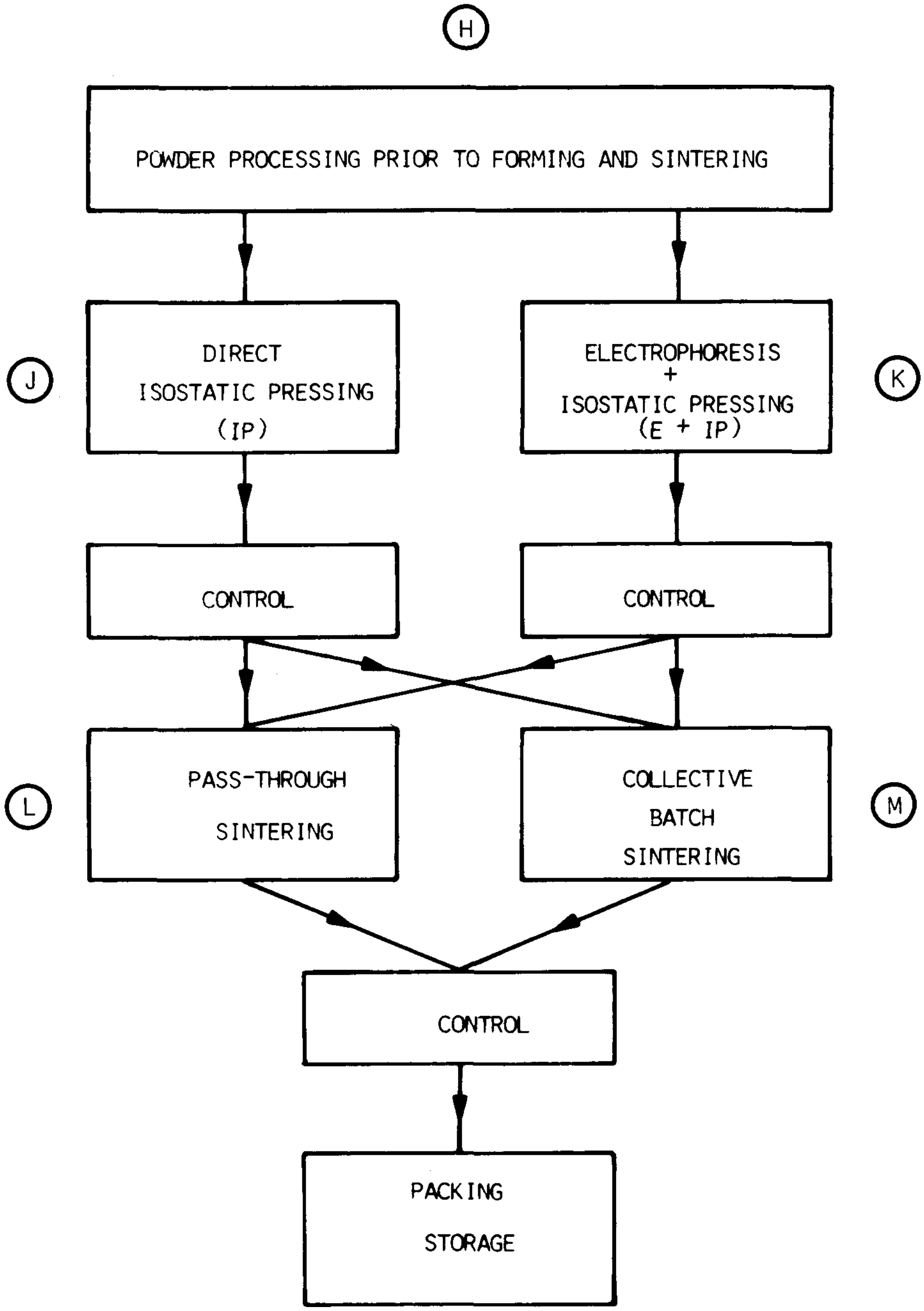

Figure A-1 - Different Manufacturing Routes Studied

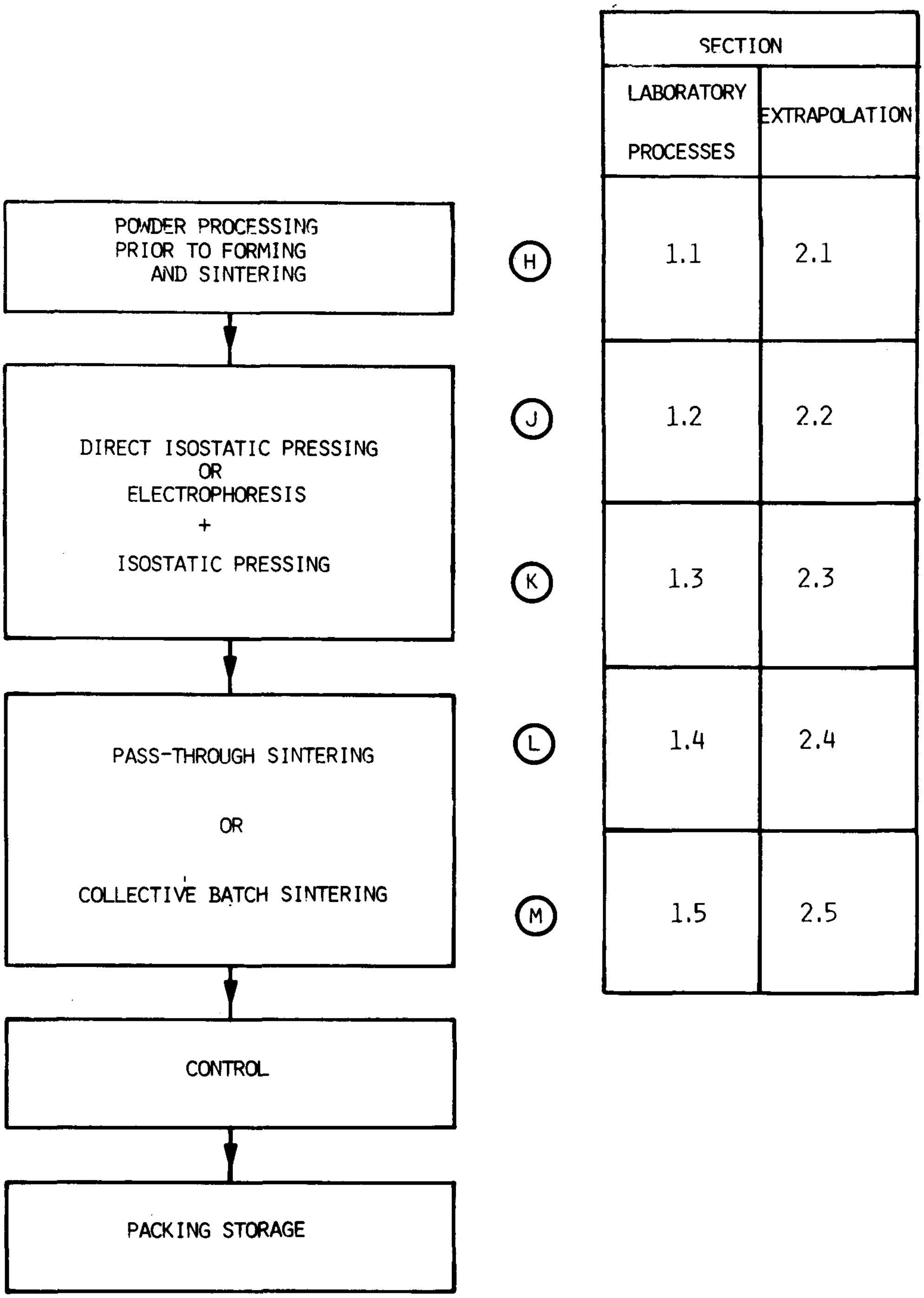

Figure A-2 - Plan of the Report

A - 2 ESTIMATE BASED UPON PROVED LABORATORY PROCEDURES

A - 2.1 Powder processing before forming and sintering

Two cases are considered :

- Fabrication routes using direct isostatic pressing : H1 J1 L1 or H1 J1 M1.
- Fabrication routes using electrophoresis plus isostatic pressing : H1 K1 L1 or H1 K1 M1.

The former case uses a granulated product ready for isostatic pressing whereas the latter uses an electrically charged product ready for electrophoretic deposition.

A - 2.1.1. Powder processing for direct isostatic pressing (H11)

Description

This process may be used with both β- and β"-alumina (see Figure A-3) for the main production steps as well as for the type of equipment used for route H11. The following raw materials are used :

- α-alumina
- Sodium carbonate
- Lithium carbonate for β"-alumina only

The raw materials, α-alumina, sodium carbonate and, for β"-alumina only, lithium carbonate, are dried to prevent agglomeration during dry blending.

Dry blending is achieved using a vibratory mill with alumina balls. The calcination synthesis is achieved at approximately 1200°C from the powder which has been put into β-alumina crucibles fabricated by a technique similar to that used for fabricating the protective walls used during sintering (see § A - 2.5). Intermediate storage after calcination synthesis does not require controlled humidity since the powder will be wet-milled before spray drying.

However, once spray-dried, the granules must be stored in a moisture-free atmosphere to prevent the development of cracks in the sintered tube.

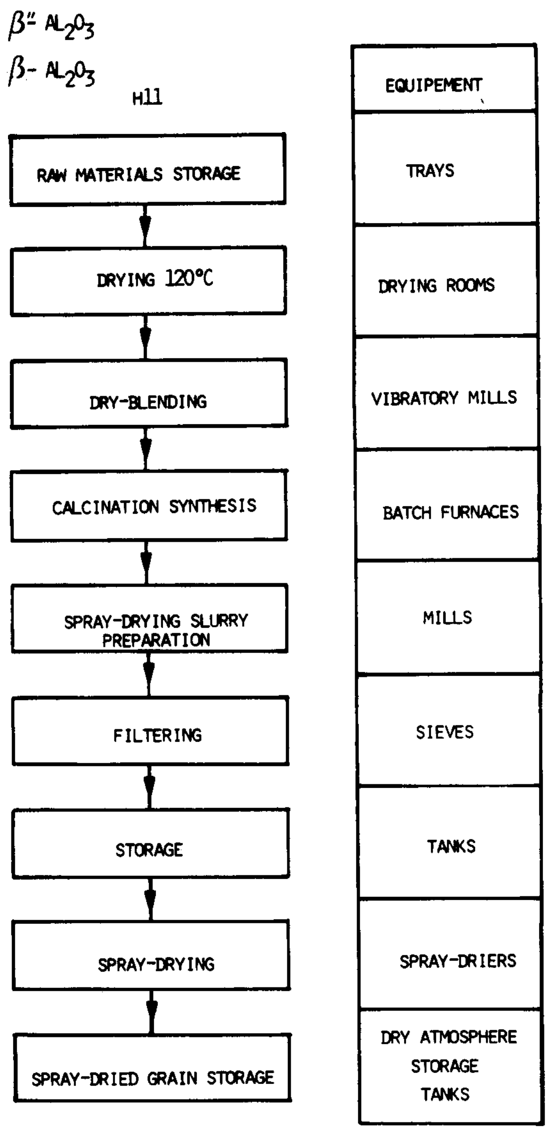

Figure A-3 - Preparation of Spray-Dried Powders

Materials and labor requirements (product yield 100 %)

5,826 kg of granules are required per day. Table A-2 lists the amounts of raw materials required for the fabrication of 100 tubes, taking into account the spray drying yield.

Detailed study of each phase has allowed estimating the time required. Assuming 100 % product yield, and two shifts, production of the granules needed for 100 tubes requires 1,002 man-hours.

Table A-2
Raw Materials Required for Production of 100 Tubes by Isostatic Pressing

	β-Alumina	β"-Alumina
α-alumina	21.07 kg	21.03 kg
Sodium carbonate	3.65 kg	3.45 kg
Lithium carbonate	-	0.40 kg

A - 2.1.2 Powder processing for electrophoresis with isostatic pressing (H12)

Description

This process is used for β-alumina only. See Figure A-4 for the main production steps as well as the type of equipment used for route H12.

The raw materials used are the same as in route H11, discussed above. The main steps are also the same as in route H11 up to the calcination synthesis stage. From this stage on, any contact with moisture should be avoided. Otherwise the powder will asborb moisture and produce problems when deposited from the electrophoresis bath. The powder is ball milled using an electrophoresis-type solvent as milling media. It is then spray-dried and the solvent recovered and recycled. The resulting granulated powder is composed of electrically charged grains, and is used both to make up the electrophoresis bath and to maintain the concentration of powder in the bath during use.

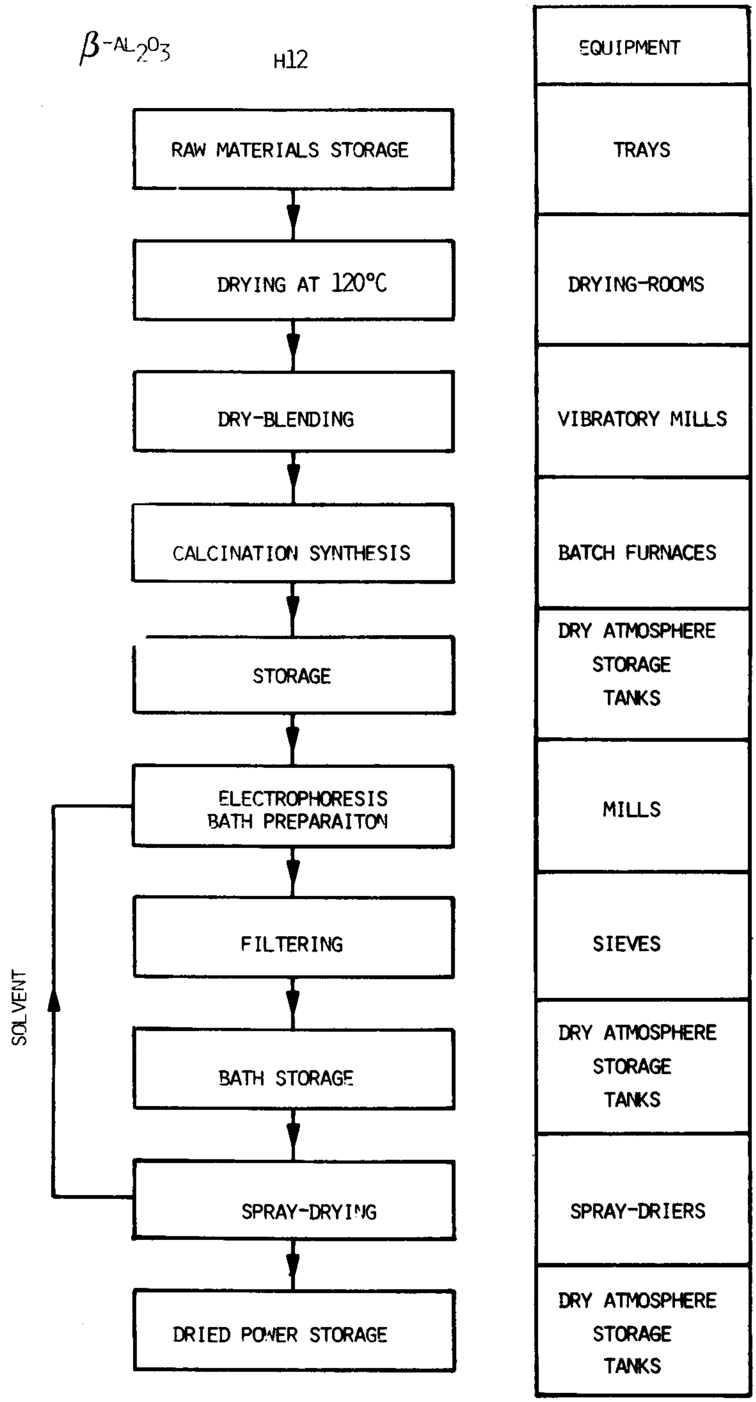

Figure A-4 - Preparation of Electrically Charged Powder for Electrophoretic Deposition

This process may appear complicated at first sight because it includes two sequential stages using solvents with a drying stage in between. But it is the only simple technique proved so far yields a reproducible wall thickness.

Materials and labor requirements

5,828 kg of electrically charged powder are required per day.

Taking product yield at the drying stage ($\frac{100}{110}$ = 90 %) into account, the amounts of raw materials necessary for 100 tubes are given in Table A-3.

Table A-3

Raw Materials Required for the Production of 100 Tubes by Electrophoretic Deposition Followed by Isostatic Pressing

	β-alumina
Alpha alumina	16.00 kg
Sodium carbonate	2.78 kg
Methylpropylketone* (MPK)	1.60 l

*Assuming that 95 % of the MPK is recovered.

Detailed study of each operation has allowed an estimate of the theoretical time required. On a two-shift basis, production of the amount of charged powder corresponding to 100 tubes requires 1.082 man-hours.

A - 2.2 Forming

Two methods of tube forming were considered :

- Direct isostatic pressing (for both β- and β"-alumina)

- Electrophoresis deposition followed by isostatic pressing (for β-alumina only)

A - 2.2.1 Direct isostatic pressing (J1)

The direct isostatic pressing technique studied is dry-bag single-action isostatic pressing. The number of presses N_p is determined by considering the following parameters :

- P : number of shifts
- N : required number of tubes per day (36,364)
- C : pressing rate (tubes per minute)
- η_{IP} : product yield

The results given in Figure A-5 use the equation :

$$N_p = \frac{1}{P} \; \frac{N}{8 \times 60} \; \frac{1}{C.\eta_{IP}} \qquad (1)$$

for the values P = 1, 2, and 3, and $0.5 \leq \eta_{IP} \leq 1$.

The pressing rate is the rated capacity of available industrial presses and depends on the times required for mold filling, pressure increase, pressure maintenance, and pressure letdown. The presses are automated except for cycle start up and demolding (removing tubes from mandrels) which are done manually. The presses are fed with powder stored in a moisture-free atmosphere. The batches are scaled.

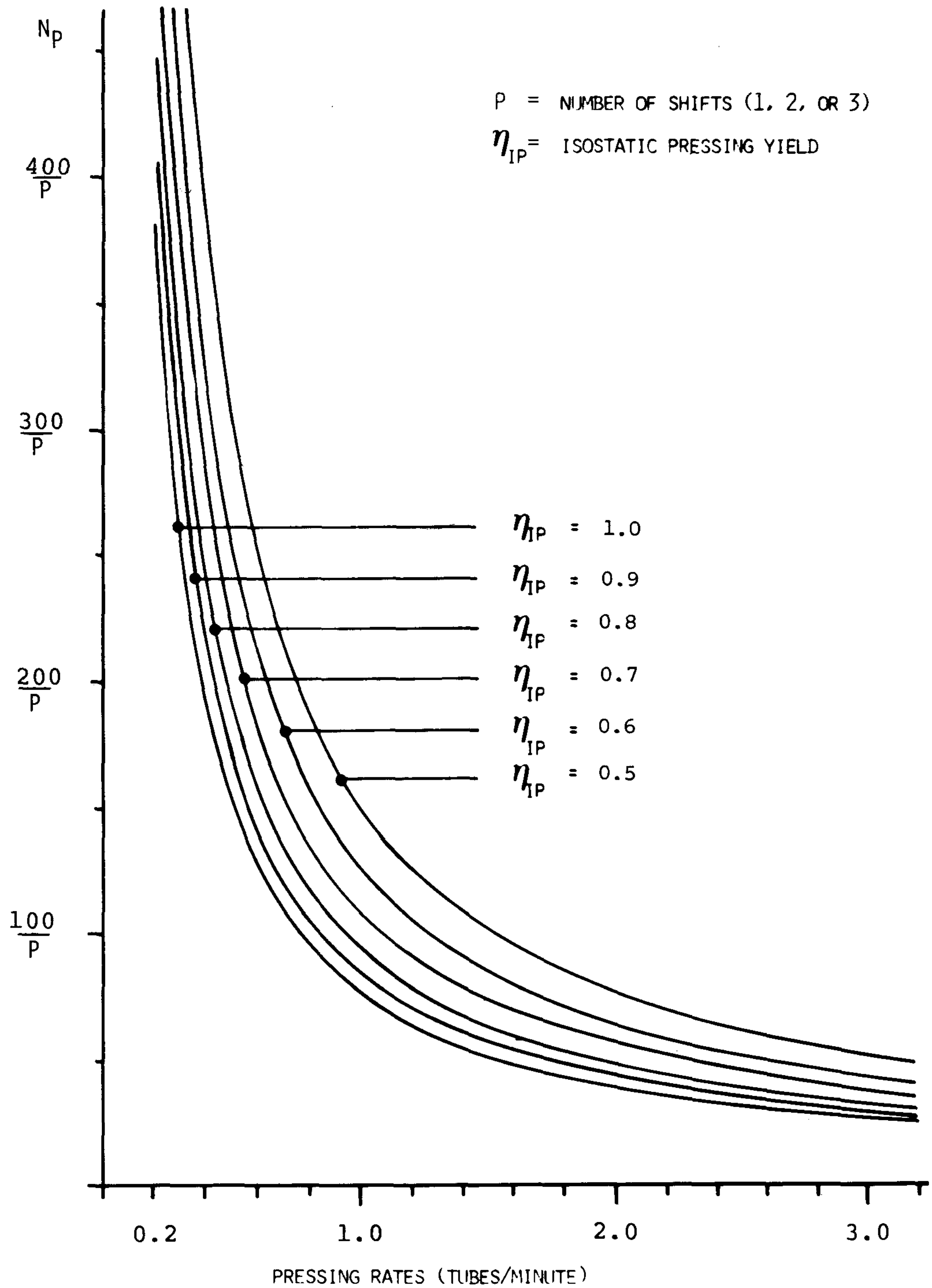

Figure A-5 - Number of Presses Versus Pressing Rate

A - 2.2.2 Electrophoresis followed by isostatic pressing (K1)

The fabrication steps are given in Figure A-6. Powder that has been electrically charged and stored in a dry atmosphere is used for making up the electrophoresis bath. The bath composition is kept constant by continuously adding charged powder and MPK in the same amounts as consumed during deposition. See Figure A-7 for a diagram of the electrophoresis deposition process.

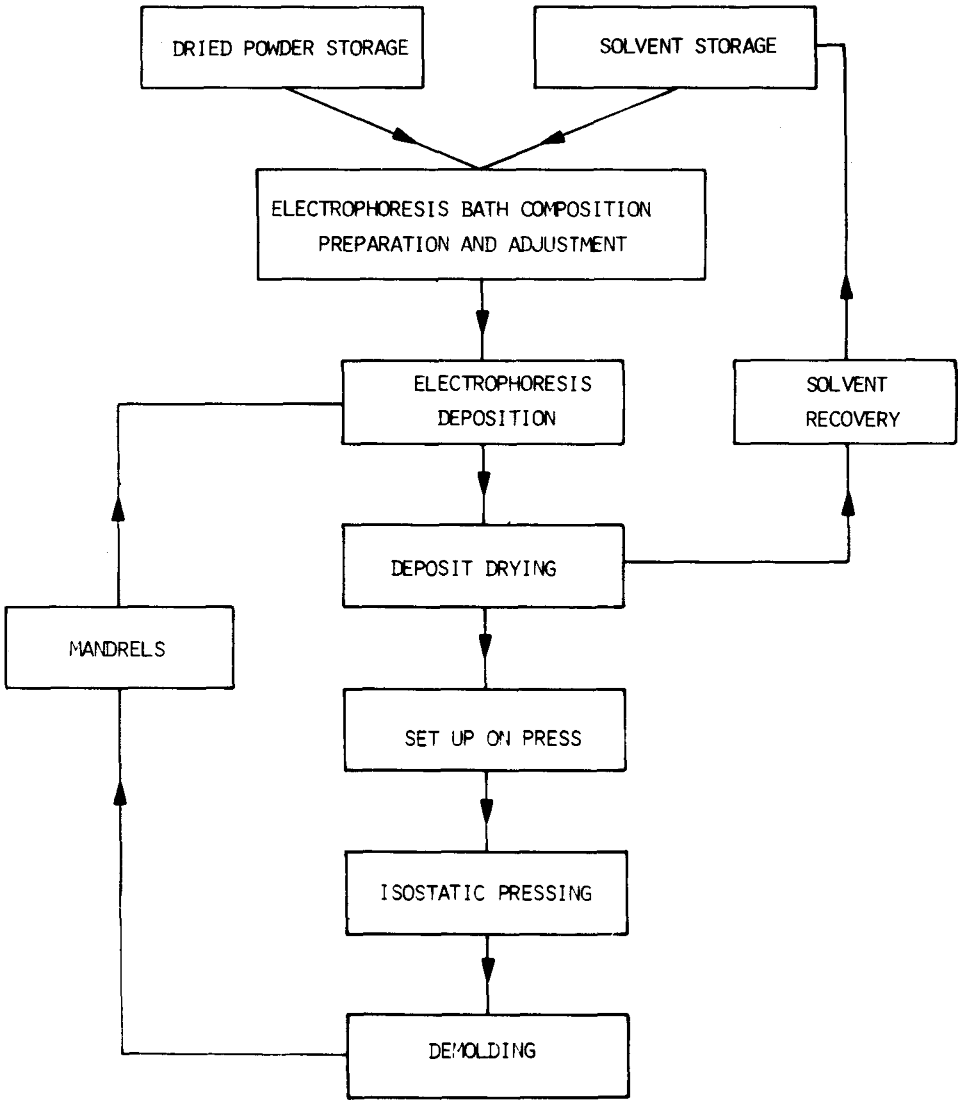

Figure A-6 - Electrophoresis Followed by Isostatic Pressing

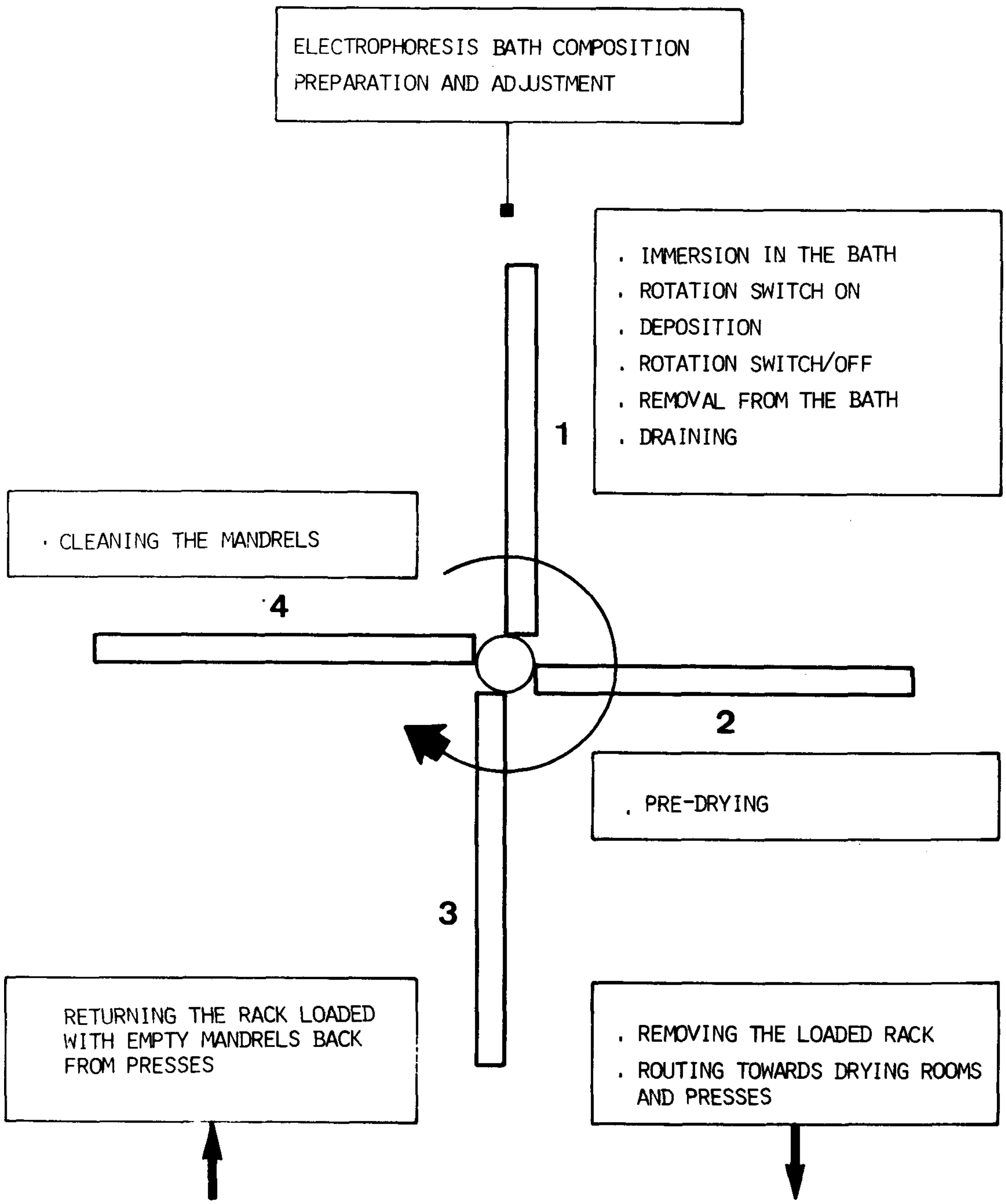

Figure A-7 - Electrophoresis

After drying and MPK recovery, the deposits are isostatically pressed by means of presses similar to those used for direct isostatic pressing. This requires inserting the deposition mandrel on a centering fixture of the isostatic press. The mandrel is then removed from the drying rack and positioned up-side down. After unmolding the pressed green tube, the mandrel is reused.

The number of mandrels required, Nm, is given by the following equation (illustrated in Figure A-8), for different values of the parameters :

$$N_m = \frac{1}{P} \frac{N}{8 \times 60} (E + D + c + I + d) \frac{1}{\eta_E \eta'_{IP}} \qquad (2)$$

The parameters are (with times expressed in minutes) :

P = number of shifts (8 hours) = 1, 2, or 3

N = required number of tubes per day (36,364)

E = electrophoretic deposition time (0.1 to 1.0)

D = drying time (30 to 180)

c = transport time (30)

I = $\frac{1}{C}$ with C = pressing time (tubes per minute) (0.25 to 2.0)

d = cleaning time (0.1)

η_E = electrophoresis yield (0.5 to 1.0)

η_{IP} = isostatic pressing yield (0.5 to 1.0)

The number of presses is determined by Eq. 1 but with a higher rate, C, than that established for direct isostatic pressing. This is because the pressing is performed on a green body of over 50 % theoretical density, permitting a faster pressure rise.

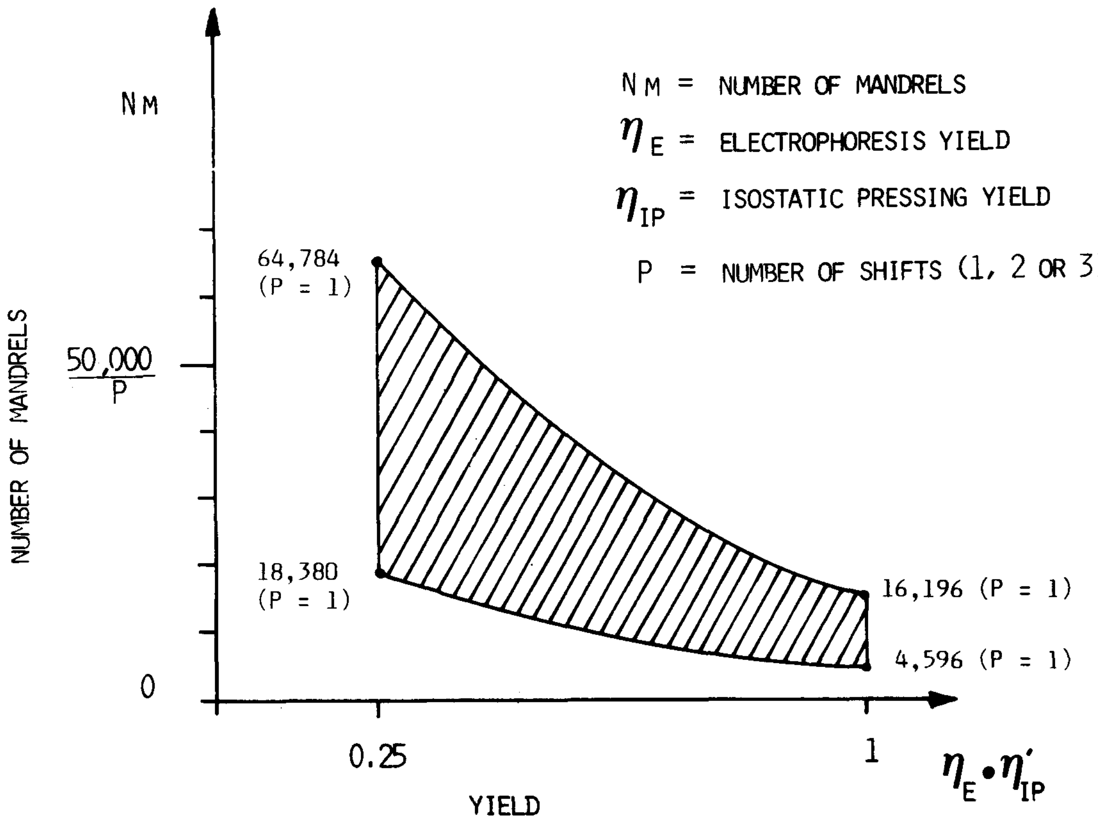

Figure A-8 - Number of Mandrels Versus the Yields of Electrophoresis and Isostatic Pressing

A - 2.2.3 Transporting the green tubes before sintering

Both forming techniques considered produce green tubes 33.7 mm outside diameter and 430 mm long. These are removed vertically from the press and then must be transported horizontally to prevent cracking. For this evaluation it is assumed that the tubes are set on trays carried by carts.

Triming and quality control take place before sintering. The tubes are trimmed by an automated diamond wheel and then manually placed on the quality control conveyer belt. They are lighted from the inside in order to reveal large defects, and then removed manually from the conveyor belt. See Figure A-9 for a detailed list of the production steps between press exit and furnace loading.

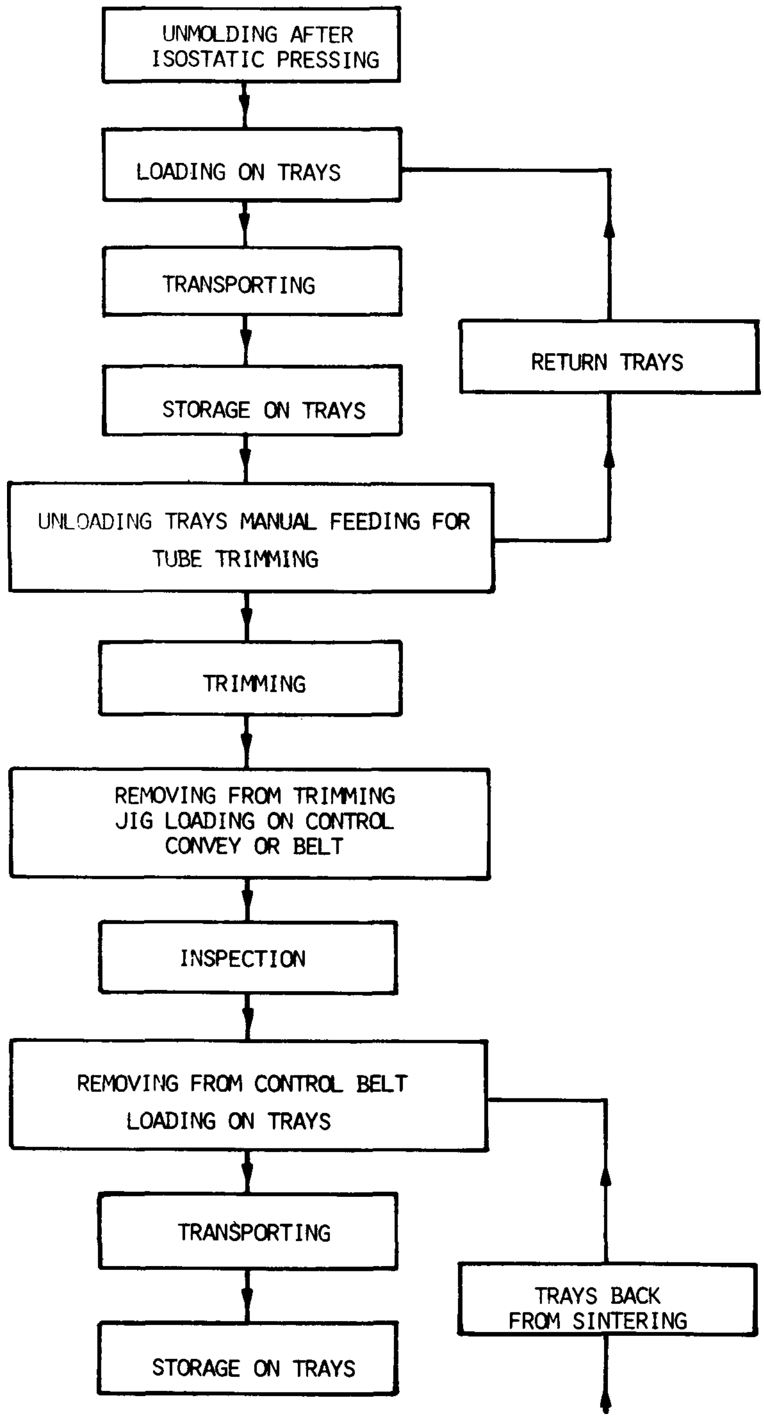

Figure A-9 - Trimming and Quality Control Before Firing

A - 2.2.4 Labor requirement

Isostatic pressing and tray loading

The manual operations at this stage are :

- Press start up
- Supervision
- Demolding the tubes
- Loading the trays

Forming 100 tubes will require 0.870 man-hours, assuming continuous 24-hour work and 100 % production yield.

Electrophoresis followed by isostatic pressing

The following operations are related to the electrophoresis process (actual deposition is automated).

- Electrophoresis start up
- Supervision
- Unloading the mandrels with their deposits from each 8-mandrel rack and setting them in the drying room
- Loading each rack holding freed mandrels on the electrophoresis assembly

The following operations are related to isostatic pressing :

- Unloading each rack holding 8 mandrels with their deposits
- Fixing the mandrel on the press

- Starting up the press
- Supervision
- Demolding the pressed tubes
- Loading the tray with the pressed tube
- Loading the rack with the freed mandrel

Assuming 100 % production yield, completing these operations for 100 tubes requires 1.846 man-hours ; 0.417 man-hours for deposition and 1.429 man-hours for pressing.

Preparation of the tubes prior to sintering

Tube preparation includes :

- Transporting the cars carrying the trays from presses to intermediate storage
- Loading the control belt
- Automatic trimming
- Quality control
- Unloading the control belt and loading the trays
- Transporting the cars to intermediate storage before sintering

Completing these operations for 100 tubes requires 0.100 man-hours for transporting the tubes before and after control and 0.980 man-hours for the actual quality control inspection. It is assumed that this stage of production will operate on a two-shift basis, requiring intermediate storage of the tubes.

A - 2.3 Sintering

Two methods of sintering are considered :

- Collective batch sintering within protective container walls for both β- and β"-aluminas.

- Pass-through sintering for β-alumina only

A discussion of pass-through sintering, only recently investigated, is included because results to date indicate that it is as promising as is batch sintering.

A - 2.3.1 Collective batch sintering equipment (M1)

Figure A-10 shows a cross section through the protective container which protects the tubes from ovality and bowing during sintering. The container walls are divided into two parts :

- External, made of aluminous concrete

- Internal, active, made of β-alumina-based concrete

The tubes are hung in a fixed position by means of α-alumina bars set across the upper part of the container. The containers are then set on furnace cars in the case of a tunnel furnace or on the sole-plate in the case of rotating-sole furnace. The containers must be transported carefully at all times during the 10-hour thermal cycle to avoid cracking the tubes. The number of rotating-sole furnaces is determined by the number of tubes that will fit in a container plus the number of containers that the furnace can handle per hour.

For example, assuming that :

- Each protective container holds 18 tubes in a 3 x 6 array

- Each furnace handles 6.2 containers per hour

- 2,677 tubes a day/furance are produced

- Production yield is 100 %

10 furnaces are required.

$$[\ \frac{36364 \times 5}{7} \times \frac{1}{2677} \approx 10\ ] \qquad (3)$$

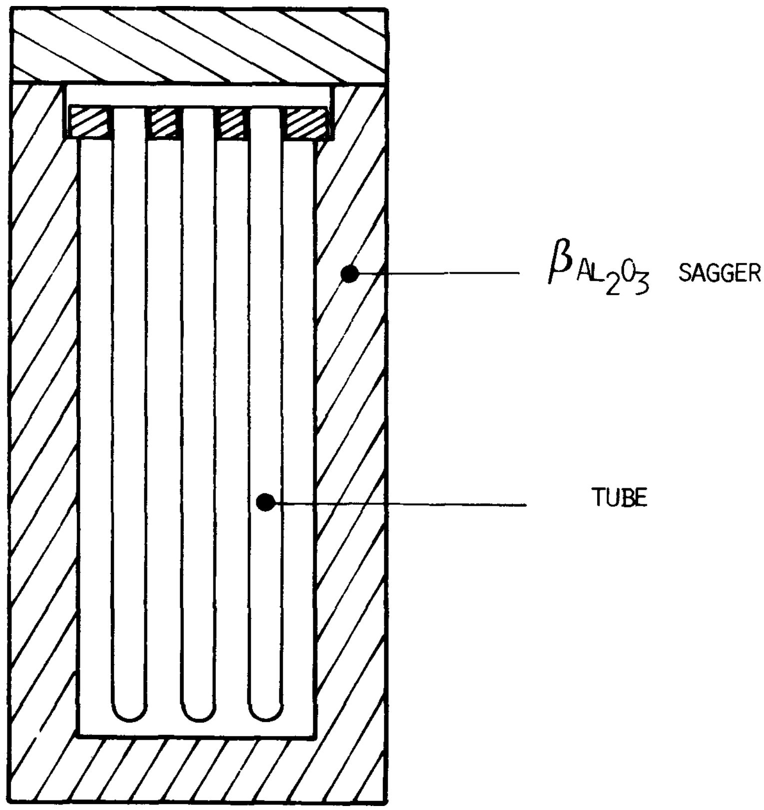

Figure A-10 - Batch Sintering Container

A - 2.3.2 Pass-through sintering equipment (L1)

Figure A-11 illustrates the pass-through sintering process. The tube is set on a centering fixture, and is loaded into the furnace from the top. It then passes vertically through a furnace heating zone and is unloaded from the bottom. The selected pass-through speed allows loading and unloading approximately every three hours for a production of 8 tubes/day/furnace assuming that the furnaces are operated continuously. The number of furnaces required is determined from the required daily output :

$$\frac{36364 \times 5}{7} \times \frac{1}{8} = 3250 \text{ (at 100 \% yield)} \qquad (4)$$

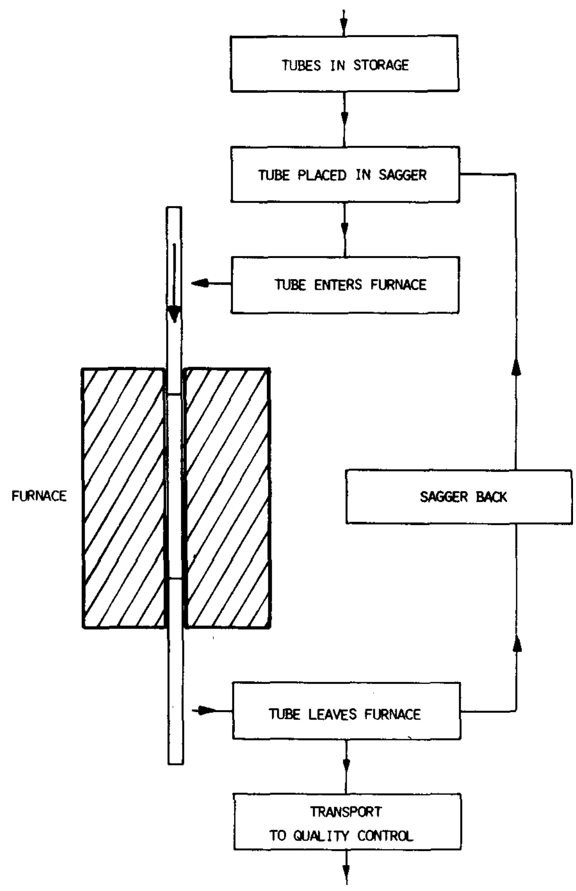

Figure A-11 - Pass-Through Sintering

A - 2.3.3 Materials and labor requirements

Collective batch sintering materials (M1)

The protective containers are made of about 40 kg β-alumina concrete and 90 kg α-alumina concrete and can be used 10 times, i.e., for sintering 180 tubes. Thus 22.2 kg of β-alumina concrete and 50 kg α-alumina concrete are used for sintering 100 tubes. The α-alumina fixture from which the tubes hang can also withstand 10 firing cycles.

Pass-through sintering materials (L1)

The centering fixture for containing the electrolyte is an α-alumina tube that can withstand 30 firing cycles.

Collective batch sintering labor (M1)

The major manual operations are loading and unloading the tubes and recovering the tube hanging fixture. The fired tubes are also manually set horizontally on mobile racks similar to those used at the forming stage. These operations require 2.03 man-hours for 100 tubes.

Pass-through sintering labor (L1)

The major manual operations are centering the green tubes when loading, and unloading the fired tubes. These operations require 4.09 man-hours for 100 tubes. For a detailed discussion, see the Appendix.

A - 2.4 Quality control labor requirement

The tubes, stored on the trays on furnace cars after sintering, are manually unloaded and placed on the quality control belt. The control operations, which follow trimming to the right length, are detailed in Part D. Inspection time for 100 tubes is estimated at 1.180 man-hours for β-alumina and 1.416 man-hours for β"-alumina.

A - 2.5 Factory cost estimate for β-alumina tubes

Labor (100 % yield)

The total time required for the fabrication of 100 tubes is given in Table A-4, along with a breakdown for major manufacturing steps, by percent.

Table A-4
Labor for the Routes Studied

Route	Labor (man-hours)	Powder preparation (%)	Shaping (%)	Sintering (%)	Control (%)	Miscellaneous (%)
H11 J1 M1	6.842	14.6	12.7	29.6	31.6	11.4
H11 J1 L1	8.902	11.2	9.8	45.9	24.2	8.8
H12 K1 M1	7.898	13.7	23.4	25.7	27.3	9.8
H12 K1 L1	9.958	10.9	18.5	41.1	21.7	7.8

This breakdown is illustrated in Figure A-12. Several conclusions are noted :

- The time consumed by powder processing is almost the same in both cases.
- The time required for forming by electrophoresis followed by isostatic pressing is considerably longer than for direct isostatic pressing.
- Sintering with the pass-through technique requires a longer total time, but produces a better yield than does batch sintering with the present state of the art.
- Quality control assumes a significant role in the process, since each tube is inspected.

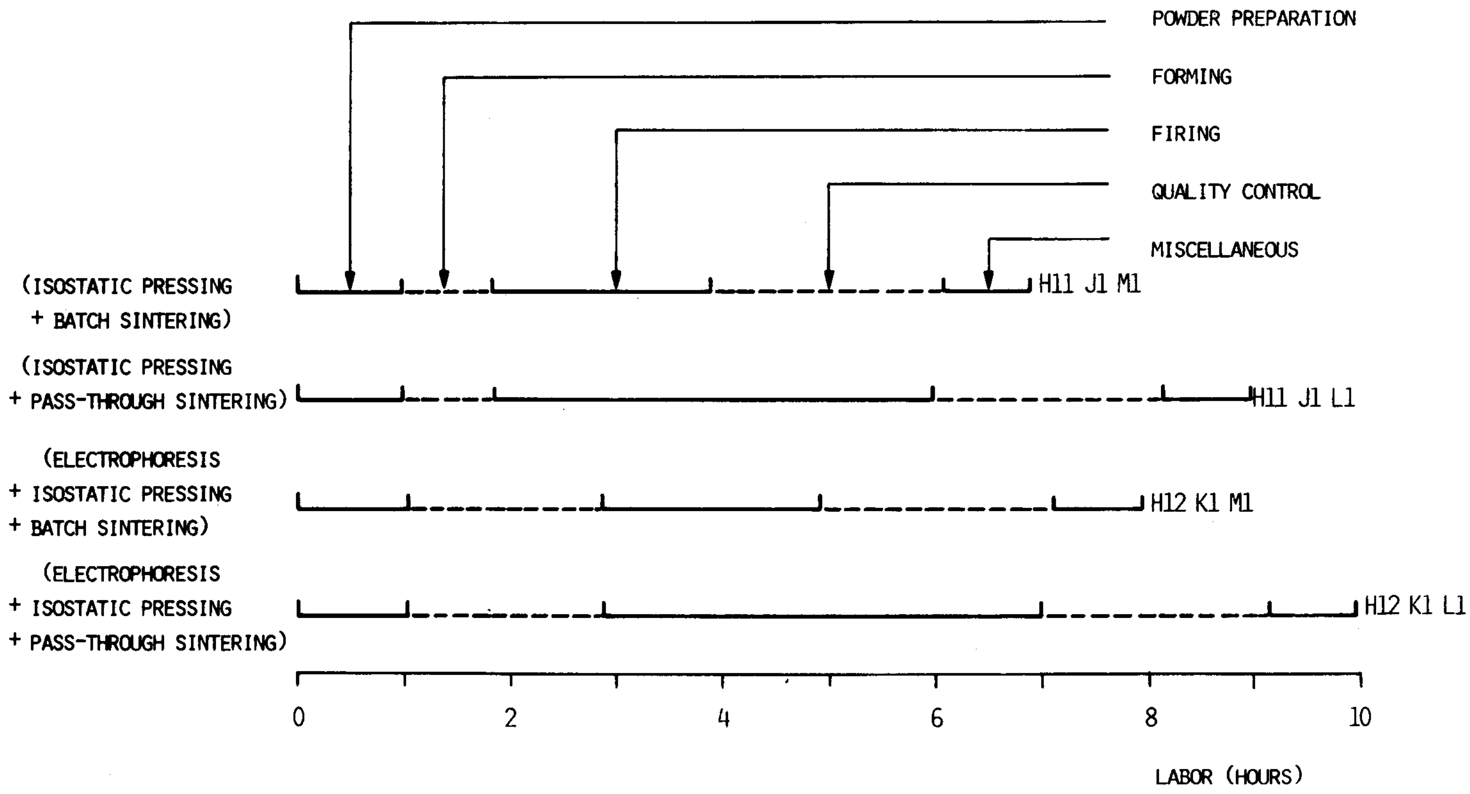

Figure A-12 - Labor for each Step of the Routes Studied for βAl_2O_3

Materials (100 % yield)

The costs of raw materials and of other materials used in the fabrication (mainly the sintering stage) or 100 tubes are given in Table A-5.

Table A-5

Cost of Materials for 100 β-Alumina Tubes by Production Route

Route	Raw materials $	Other materials $
H11 J1 M1	13.2	147.7
H11 J1 L1	13.2	292.7
H12 K1 M1	18.5	147.7
H12 K1 L1	18.5	292.7

It should be noted that the material cost for pass-through sintering is nearly twice that for collective batch sintering. This is accounted for by direct use in the laboratory process of α-alumina tubes to hold the electrolyte tubes and to prevent ovality and bowing during firing. This cost is eliminated in the extrapolation of the laboratory process (see section A - 3.5).

Assessment of equipment costs and of rent

The equipment required for the fabrication of 8,000,000 tubes a year has been estimated assuming certain production rates, number of workshifts, and an overall product yield of 75 % as suggested by Arthur D. Little guidelines. The equipment investment has been determined on the basis of commercial equipment (for spray drying, isostatic pressing, batch sintering and control lines) or anticipated equipment (for electrophoresis and pass-through sintering). The type of equipment chosen determined the work areas ; allowance was made for the areas required for raw materials, intermediate storage, and access. The equipment costs and floor areas required are given in Table A-6.

The remarkable differences in equipment costs are due mainly to the type of sintering selected : pass-through sintering requires much more capital investment than batch sintering.

Table A-6
Equipment Costs and Areas for
β-Alumina by Production Route

Routes	Areas Square Meter	Square Feet	Investments $ million
H11 J1 M1	13,200	142,000	31.5
H11 J1 L1	19,600	211,000	63.2
H12 K1 M1	15,000	162,000	30.5
H12 K1 L1	21,300	230,000	62.4

Factory cost (75 % yield)

The factory cost is calculated following the Arthur D. Little guidelines ; most importantly, the assumption of 75 % product yield. The components of the factory cost for 100 β-alumina tubes are given in Table A-7. The highest costs are incurred by those routes using continuous sintering, which requires more labor and capital investment.

A - 2.6 Selling price of β-alumina tubes (75 % yield)

The selling price is the sum of the factory cost, the taxes, and the after-tax return on investment in working capital, the machinery, and its installation (see Table A-8).

Table A-7

Factory Cost for β-Alumina
in U.S. $ by Production Route

Route	Labor	Materials and purchased components	Overhead on labor	Overhead on Materials	Equipment depre-ciation	Rent	Factory cost
H11 J1 M1	91.30	214.5	136.95	21.45	49.22	8.88	522.30
H11 J1 L1	118.70	407.9	178.05	40.79	98.75	13.19	857.38
H12 K1 M1	105.30	221.6	157.95	22.16	47.66	10.13	564.80
H12 K1 L1	132.80	415.0	199.20	41.50	97.50	14.38	900.38

Table A-8

Selling Prices of 100 β-Alumina
Tubes by Production Route

Route	Selling price $
H11 J1 M1	717
H11 J1 L1	1,231
H12 K1 M1	759
H12 K1 L1	1,274

A - 2.7 Factory cost estimate for β"-alumina tubes

The only fabrication route investigated involves forming by direct isostatic pressing and batch sintering (H11 J1 M1). Other forming and sintering techniques have been insufficiently tested for β"-alumina to warrant consideration.

Labor (100 % yield)

The man-hours required for the fabrication of 100 β"-alumina tubes are detailed in Table A-9 alongside the man-hours required for β-alumina. The quality control and handling and storing portions consume more time for β"-alumina because handling must be done in a moisture-free atmosphere.

Table A-9

Comparison of Labor Costs for β- and β"-alumina Tubes

H11 J1 M1	Labor man-hours	Powder preparation %	Shaping %	Sintering %	Control %	Miscellaneous %
β"Al_2O_3	7.214	13.9	12.1	28.1	33.2	12.7
βAl_2O_3	6.842	14.6	12.7	29.6	31.6	11.4

Materials (100 % yield)

The cost of the raw materials and other materials needed for the manufacture of 100 tubes is detailed in Table A-10 in comparison with the costs of β-alumina. The difference between the raw materials costs is accounted for by the use of lithium carbonate for stabilizing the β"-alumina.

Table A-10

Comparison of Materials Costs for β- and β"-alumina Tubes

H11 J1 M1	Raw materials $	Other materials $
β"Al_2O_3	18.3	147.7
βAl_2O_3	13.2	147.7

Equipment investments and areas (75 % yield)

The floor area and cost of equipment are given in Table A-11 in comparison with those required for the use of β-alumina. The difference between the investments is due to the use of moisture-free rooms for control and storage of the β"-alumina after sintering.

Table A-11

Comparison of Equipment Cost and Area for β- and β"-alumina Tubes

	Areas		Investments
H11 J1 M1	Square meter	Square feet	$ million
β"Al_2O_3	13,950	150,000	34.9
βAl_2O_3	13,200	142,000	31.5

Factory cost (75 % yield)

The factory cost and its components for the production of 100 tubes are given in Table A-12 in comparison with β-alumina. The factory cost of β"-alumina is approximately 5 % greater than that of β-alumina. This is not a significant difference and is accounted for by the moisture sensitivity of β"-alumina once fired. The operations that take place before sintering are quite similar in both cases.

Table A-12

Comparison of Factory Cost for β- and β"-alumina Tubes

H11 J1 M1	Labor	Materials and purchased components	Overhead on labor	Overhead on materials	Equipment depre-ciation	Rent	Factory cost
β"Al_2O_3	96.20	221.40	144.30	22.14	54.53	9.38	547.95
βAl_2O_3	91.30	214.50	136.95	21.45	49.22	8.88	522.30

A - 2.8 Selling price of β"-alumina Tubes (75 % yield)

The selling price of 100 β"-alumina tubes is given in Table A-13 in comparison with the price of β-alumina.

Table A-13
Comparison of the Selling Prices of 100
β- or β"-alumina Tubes

H11 J1 M1	Selling price $
$\beta''Al_2O_3$	775
βAl_2O_3	717

A - 2.9 Review and remarks

The selling prices of 100 tubes of β- and β"-alumina are given in Figure A-13 by production route. The highest prices are found in the routes that use continuous sintering. For a given route, the difference caused by the forming technique chosen (E + IP or direct IP) is not significant. It should be noted that these calculations assume an overall product yield of 75 %. In our opinion, this yield looks high for the routes using batch sintering, hence their selling prices should be increased. Correspondingly, the yield looks low for the routes using continuous sintering, hence their selling prices should be lowered. Therefore, the real difference in costs should be considered smaller than the difference estimated.

The energy required for fabrication (the most energy-consuming process is the sintering) is estimated at 3.5 therm/tube for batch sintering and 5 therm/tube for continuous sintering. In the case of electrical furnaces this results in a consumption of 4 KWh/tube and 5.8 KWh/tube, respectively. Taking into account the current electricity price in France increases the selling price for 100 tubes by $30 and $43.5, respectively. The use of natural gas as the energy source would reduce these costs by a factor of 3.

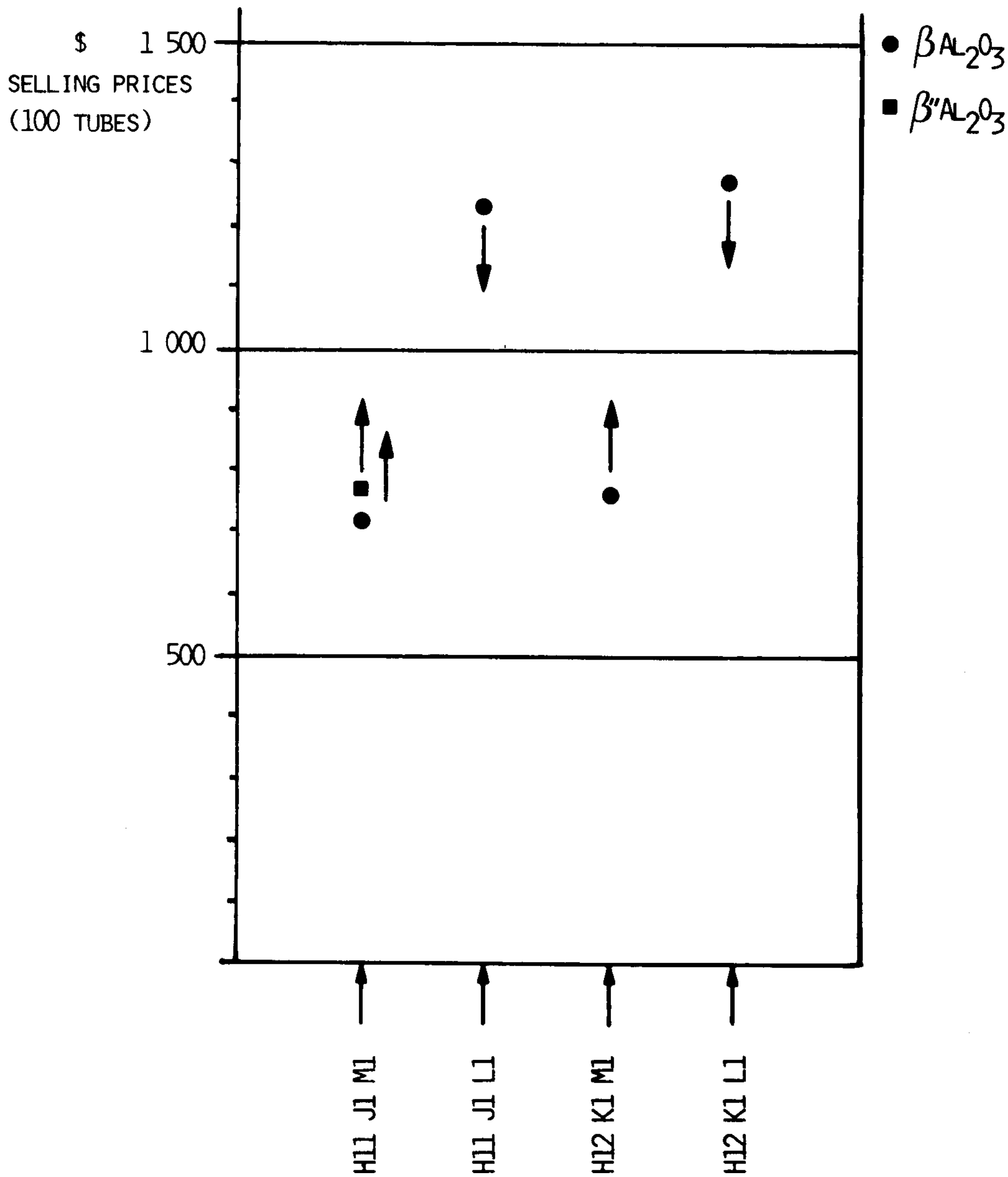

Figure A-13 - Selling Prices of 100 Tubes Plotted by Manufacturing Routes
(the Arrows Reflect the Impact Actual Yields have on Selling Price)

A - 3 ESTIMATE FOR EXTRAPOLATION OF THE LABORATORY PROCESSES

The results reported in § A - 2 lead us to focus on the routes H21 J2 L2 and H22 K2 M2 as applied to β-alumina.

H21 J2 L2 includes :

- Powder preparation by continuous process prior to isostatic pressing (H21)
- Forming by direct isostatic pressing (J2)
- Pass-through sintering with the use of an improved technique (L2)

It will be compared to the route H11 J1 L1.

H22 K2 M2 includes :

- Powder preparation by continuous process prior to electrophoresis (H22)
- Forming by electrophoresis deposition without isostatic pressing (K2)
- Batch sintering with a more efficient use of protective container walls (M2)

It will be compared to the route H12 K1 M1.

A - 3.1 Product processing before forming and sintering

Description

The continuous fabrication process includes :

- Continuous drying, scaling, batching of raw materials
- Continuous blending

- Continuous synthesis calcination in an inclined revolving tube furnace lined with Jargal type electrocast refractory bricks

- Continuous preparation of slip before spray drying

- Conventional spray drying yielding granules for direct isostatic pressing or closed-loop spray drying (including recovery of solvent) yielding electrically charged granules.

- Storage of the powder in a dry atmosphere after spray drying

Estimate

Raw materials

The required quantities of raw materials are similar to those listed in § A - 1.1 and A - 1.2. See Table A-14 for the amounts required to produce 100 tubes at 100 % yield. It should be noted that the differences are due to the differences in spray drying yields : 69 % for the spray drying for isostatic pressing and 90 % for the spray drying for electrophoresis.

Table A-14
Raw Materials Required for Production of 100 Tubes

	H21 Isostatic pressing	H22 Electrophoresis
α-alumina	21.07 kg	16.00 kg
Sodium carbonate	3.65 kg	2.78 kg
M.P.K.	-	1.6 l

A - 3.2 Shaping

A - 3.2.1 Direct isostatic pressing (J2)

The method of isostatic pressing presented in § A - 2.2.1 is retained : production rates and shift number are the same. But manual transporting of the tubes is eliminated by using a conveyor with suspended trays, reducing the time required for handling.

A - 3.2.2 Electrophoresis deposition (K2)

Refer to Figure A-14 for the main steps in electrophoresis deposition. The method of maintaining constant bath composition is the same as detailed in § 2.2. After drying and recovering the solvant, the green tube is demolded without pressing and placed on a tray on the conveyor belt.

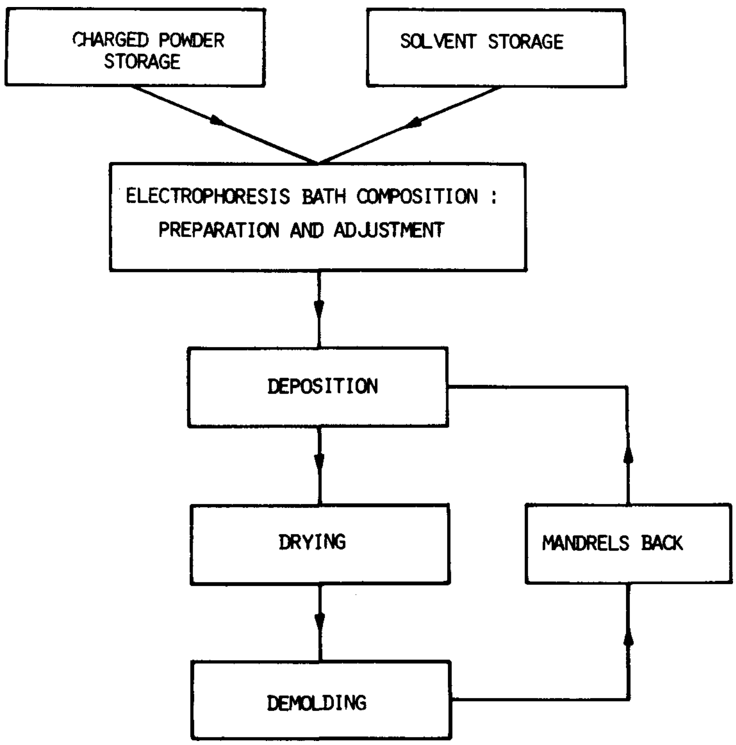

Figure A-14 - Forming by Electrophoresis without Isostatic Pressing

A - 3.2.3 Preparation of the tubes before sintering

Tube preparation is the same as previously described in §A - 2.2.3 and requires the same amount of time up to inspection. At this point the handling time is reduced by the use of a suspended-tray conveyor system.

A - 3.2.4 Labor requirement for 100 tubes (100 % yield)

Table A-15 gives the time required in comparison with those estimated in § A - 1.

Table A-15

Labor for Forming, Handling and Control after Extrapolation

Isostatic pressing	J2 : 0.870 h	J1 : 0.870 h
Electrophoresis	K2 : 0.617 h	K1 : 1.846 h (+ Isostatic pressing included)
Handling	0.100 h	0.032 h
Control	0.980 h	0.980 h

A - 3.3 Sintering

A - 3.3.1 Improved batch sintering (M2)

The method of batch sintering is the same as shown in Figure A-10, and uses the same fixture for holding the tubes within the protective container. However, the lifetime of the protective container is considered as twice as long.

A - 3.3.2 Improved pass-through sintering (L2)

A diagram of the furnace used in improved pass-through sintering is given in Figure A-15 ; the furnace is loaded from the top and unloaded from the bottom. The process is basically sequential sintering done in a multi-pass-through furnace, ensuring that all the tubes have the same thermal history. This saves labor as well as sintering materials.

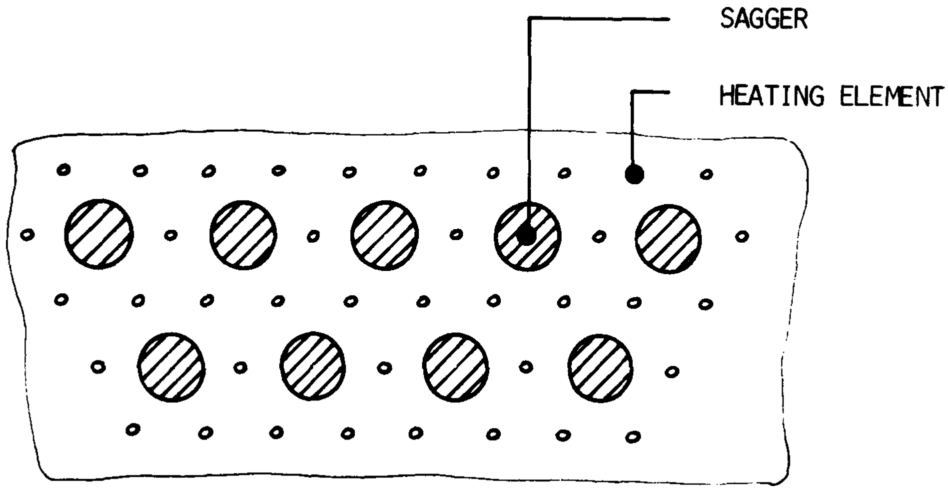

Figure A-15 - Cross Section of Multi Pass-through Furnace

A - 3.3.3 Materials and labor requirements

The quantities of materials needed for 100 tubes at 100 % yield are given in Table A-16 in comparison with those estimated in § A - 1.

Table A-16
Materials Before and After Extrapolation

Batch sintering βAl_2O_3 concrete	Batch sintering αAl_2O_3 concrete	Pass-through sintering Materials
M1 : 22.2 kg	M1 : 50.0 kg	L1 : support tube
M2 : 11.1 kg	M2 : 25.0 kg	L2 : separator

The man-hours required for sintering 100 tubes at 100 % yield are given in Table A-17 in comparison with those estimated in § A - 1.

Table A-17
Labor for Sintering Before and After Extrapolation

Batch sintering	Pass-through sintering
M2 : 2.03 h	L2 : 2.045 h
M1 : 2.03 h	L1 : 4.09 h

A - 3.4 Control

The tubes are inspected as described in Part D. The labor required is the same as previously determined : 1.180 man-hours. However, the handling times are lowered by the use of the suspended-tray conveyor system.

A - 3.5 Factory cost assessment

Labor (100 % yield)

The time required for the fabrication of 100 tubes is detailed in Table A-18, in comparison with that estimated in § A - 1.

Table A-18

Labor Cost Before and After Extrapolation

Route	Labor (hours)	Powder Preparation %	Shaping %	Sintering %	Control %	Miscellaneous %
H21 J2 L2	6.003	5.6	14.4	34.1	36.0	9.9
H11 J1 L1	8.902	11.2	9.8	45.9	24.2	8.8
H22 K2 M2	5.762	6.3	10.7	35.2	37.5	10.3
H12 K1 M1	7.898	13.7	23.4	25.7	27.3	9.8

Figure A-16 illustrates the costs in comparison with those previously determined. The labor time (cost) is reduced about 30 % in the extrapolated production processes.

Materials (100 % yield)

The costs of raw materials and other materials used for tube fabrication of 100 tubes are given in Table A-19 in comparison with those previously determined. Cost improvements result from lower sagger and container requirements for the sintering step.

Table A-19

Materials Cost Before and After Extrapolation

Route	Raw materials $	Other materials $
H21 J2 L2	13.2	36.6
H11 J1 L1	13.2	292.7
H22 K2 M2	18.5	73.85
H12 K1 M1	18.5	147.7

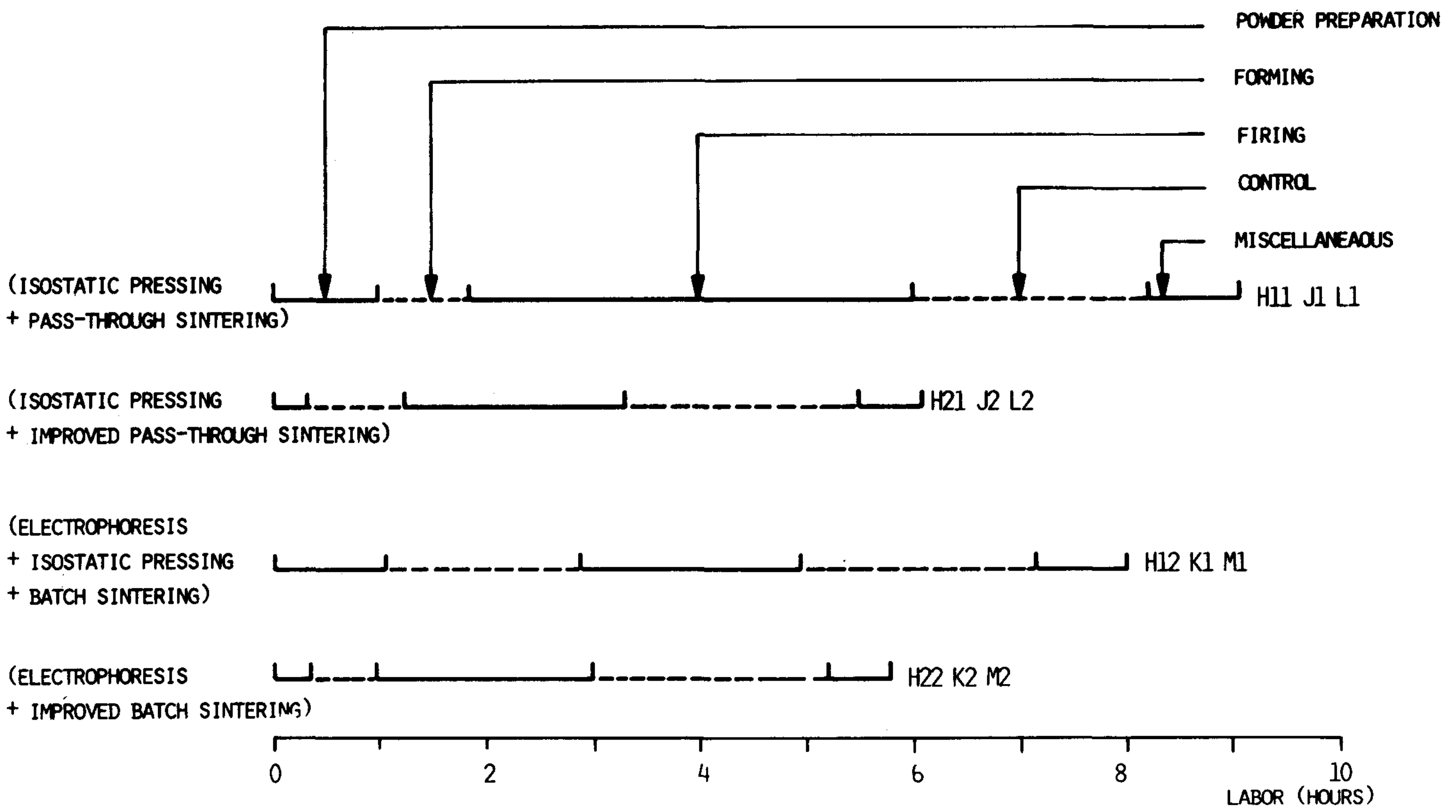

Figure A-16 - Labor for each Step after Extrapolation of the Laboratory Process

Assessment of the equipment costs (75 % yield)

Equipment costs and the work areas required are given in Table A-20 in comparison with those determined in § A - 1. The work areas remain the same and are simply repeated.

The increase in cost is largely due to :

- The continuous powder preparation
- The automated conveyor system
- Modifying the interior of the pass-through furnaces

Table A-20

Equipment Cost and Areas
Before and After Extrapolation

Route	Investments $ million	Areas Square feet
H21 J2 L2	89.66	211,000
H11 J1 L1	63.2	211,000
H22 K2 M2	43.99	162,000
H12 K1 M1	30.5	162,000

Factory cost assessment (75 % yield)

The factory cost for 100 tubes is detailed in Table A-21 in comparison with that estimated in § A - 1. The most significant result of use of the pass-through technique is the reduction of factory cost by a factor of 2. This results, in large part, from the improved efficiency of saggers/containers used in the sintering step.

Table A-21

Factory Cost Before and After Extrapolation (in $)

Route	Labor	Materials and purchased components	Overhead on labor	Overhead on materials	Equipment depre-ciation	Rent	Factory cost
H21 J2 L2	80.04	66.35	120.06	6.64	140.10	13.19	426.38
H11 J1 L1	118.70	407.90	178.05	40.79	98.75	13.19	857.38
H22 K2 M2	76.83	123.09	115.25	12.31	68.73	10.13	406.34
H12 K1 M1	105.30	221.60	159.95	22.16	47.66	10.13	564.80

A - 3.6 Selling price (75 % yield)

The selling price for 100 tubes is given in Table A-22 according to the route used in comparison with that calculated in § A - 1. Figure A-17 illustrates the price comparison.

Table A-22

Selling Prices Before and After Extrapolation

Route	Selling price $
H12 J2 L2	885.08
H11 J1 L1	1,230.80
H22 K2 M2	649.06
H12 K1 M1	758.60

A - 3.7 Review

As noted in § A - 2.9, an overall product yield of 75 % appears high for the routes using batch sintering and low for the routes using continuous sintering. The selling prices should thus be adjusted accordingly and the difference between the routes considered slightly smaller. Most importantly, improved pass-through sintering appears to substantially lower the selling price and merits further investigation.

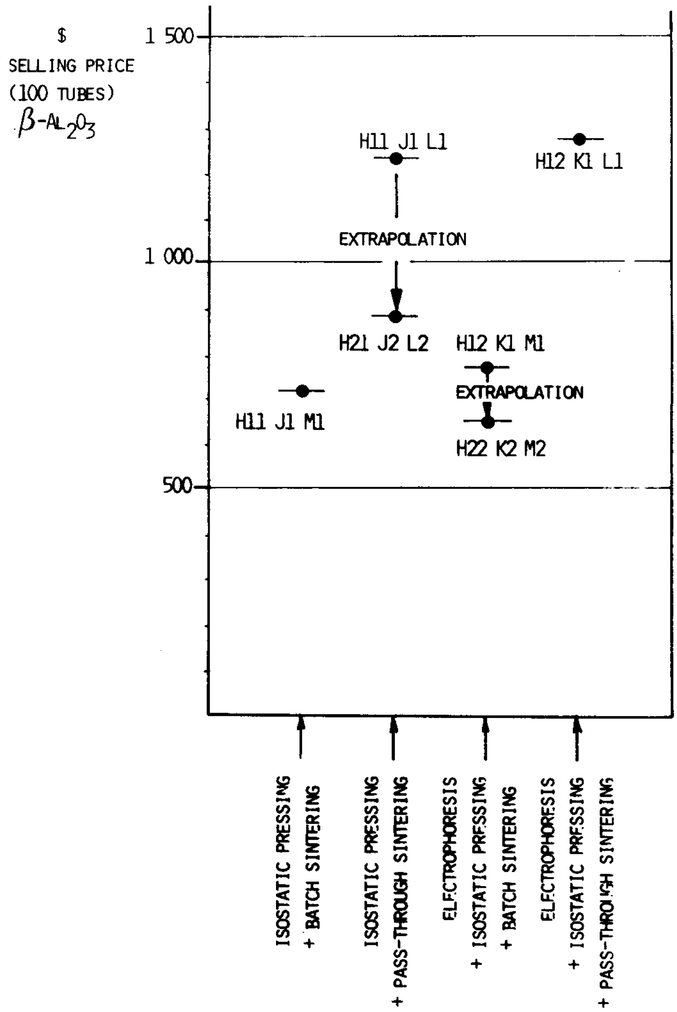

Figure A-17 - Comparison of Selling Prices for 100 Tubes after Extrapolation of the Laboratory Process

Part B

COST ESTIMATE FOR BETA"-ALUMINA

CONTENTS

ILLUSTRATIONS

TABLES

COST ESTIMATE FOR β"-ALUMINA

B - 1 INTRODUCTION

This study applied the technique used in RP726-1 for β-alumina. Various fabrication routes were considered and applied to different tube sizes. The goal was to estimate the selling prices of β"-alumina tubes. Part C deals with this comparison. The guidelines used in this estimate are those recommended by Arthur D. Little ; however, overall product yield should not be considered independent of tube size. We may anticipate higher yield for small tubes and lower yield for large tubes. Unlike the routes studied in Part A, the fabrication routes discussed here for β"-alumina are not all based on proved laboratory procedures.

B - 2 DIMENSIONS OF THE TUBES CONSIDERED

Table B-1 presents the dimensions of the tubes considered. The numerical designators are the same as in RP726-1. It should be noted that the tube considered in Part A would be located between tubes 3 and 4.

Table B-1

Dimensions of the Five Tubes Considered

Tube	Diameter (cm)	Length (cm)	Wall thickness (mm)	Active area (cm^2)
1	1.0	15	0.7	47
2	1.5	22	0.7	103
3	2.0	32	1.0	201
4	2.9	44	1.5	400
5	3.6	53	2.0	599

B - 5 FORMING

The tubes are formed as described in Part A (§ A - 2.2).

Electrophoresis followed by isostatic pressing (B)

The labor total is determined by :

- The number of mandrels per electrophoresis machine
- The cycle duration of isostatic pressing after drying (assuming one worker/four presses)

The labor required is broken down in Table B-5 for 100 tubes (at 100 % yield). One worker supervises four presses for tubes 1, 2, and 3 ; two presses for tube 4 ; and one press for tube 5.

Table B-5

Labor for Step B

	ELECTROPHORESIS FOLLOWED BY ISOSTATIC PRESSING				TOTAL LABOR (B)
Tube	Number mandrels per rack	Labor (hours)	Timing (seconds)	Labor (hours)	(hours)
1	24	0.139	52	0.454	0.593
2	18	0.185	56	0.490	0.675
3	10	0.333	70	0.613	0.946
4	6	1.049	90	1.478	2.527
5	4	2.434	102	2.606	5.041

Isostatic pressing (G)

The labor is calculated from the duration of the pressing cycle (one worker supervising four presses for tubes 1, 2, and 3 ; three presses for tube 4 ; and two presses for tube 5). The time required per tube, production rate per worker per hour (allowing for maintenance, legal breaks and number of presses), and the labor required for 100 tubes are given in Table B-6.

Table B-6

Labor For Step G

Tube	Timing (seconds)	Production per worker per hour (tubes)	Labor (hours)
1	65	176	0.568
2	70	163	0.613
3	88	128	0.781
4	112	82	1.215
5	128	41	2.424

B - 6 SINTERING

The tubes are sintered as described in § B - 3.

Batch sintering (D)

The capacity of the protective containers, the quantities of materials used for the fabrication of these containers (α-alumina and β-alumina concretes), and the container cost calculated for 100 tubes, are given in Table B-7 (100 % yield). It is assumed that the protective containers will be used 10 times. The labor required for handling 100 tubes is given in Table B-8 (assuming 100 % yield).

Table B-7

Costs For Step D

Tube	Tubes/bar	Number of bars	Number of tubes/ container	α-Al_2O_3 concrete per 100 tubes (kg)	β-Al_2O_3 concrete per 100 tubes (kg)	Purchased components per 100 tubes ($)
1	6	12	72	6.8	2.6	40.244
2	5	8	40	9.6	6.2	60.000
3	4	7	28	17.0	11.3	96.463
4	3	6	18	34.0	23.2	166.341
5	2	5	10	71.4	49.1	309.268

Table B-8

Labor For Step D

Tube	Labor (hours)
1	0.812
2	1.191
3	1.732
4	2.382
5	2.869

Pass-through sintering (E)

The materials and labor required for 100 tubes are given in Table B-9 (assuming 100 % yield).

Table B-9

Materials and Labor For Step E

Tube	Purchased components ($)	Labor (hours)
1	43.902	1.636
2	95.122	2.399
3	182.927	3.490
4	342.439	4.799
5	526.829	5.780

B - 7 QUALITY CONTROL

According to the Arthur D. Little guidelines, the cost of quality control is to be included as a separate element in the factory cost. The quality control labor required for 100 tubes is given in Table B-10 (includes inspection of each tube after shaping and after sintering for leak tightness, appearance, geometrical characteristics, and burst strength).

Table B-10

Labor For Control

Tube	Control after shaping (hours)	Control after shaping (hours)	Labor for the whole control
1	0.392	0.472	0.864
2	0.574	0.692	1.266
3	0.834	1.007	1.841
4	1.149	1.384	2.533
5	1.385	1.667	3.052

B - 8 ASSESSMENT OF THE FACTORY COST

Labor

The total time required for the fabrication of 100 tubes of various dimensions is given in Table B-11 by route. A detailed breakdown is given in Figure B-1 for powder preparation, shaping, sintering, and quality control. Relative values are given in Figure B-2 and B-3. It is important to note the substantial labor time required for inspection (a result of inspecting each tube) and for pass-through sintering.

Table B-11

Labor by Route and Dimensions (in hours)

Route	Tube 1	Tube 2	Tube 3	Tube 4	Tube 5
GFD	2.625	3.682	5.413	8.032	10.567
GFE	3.449	4.890	7.171	10.449	13.478
GBD	2.656	3.906	6.018	9.700	13.786
GBE	3.480	5.114	7.776	12.117	16.697

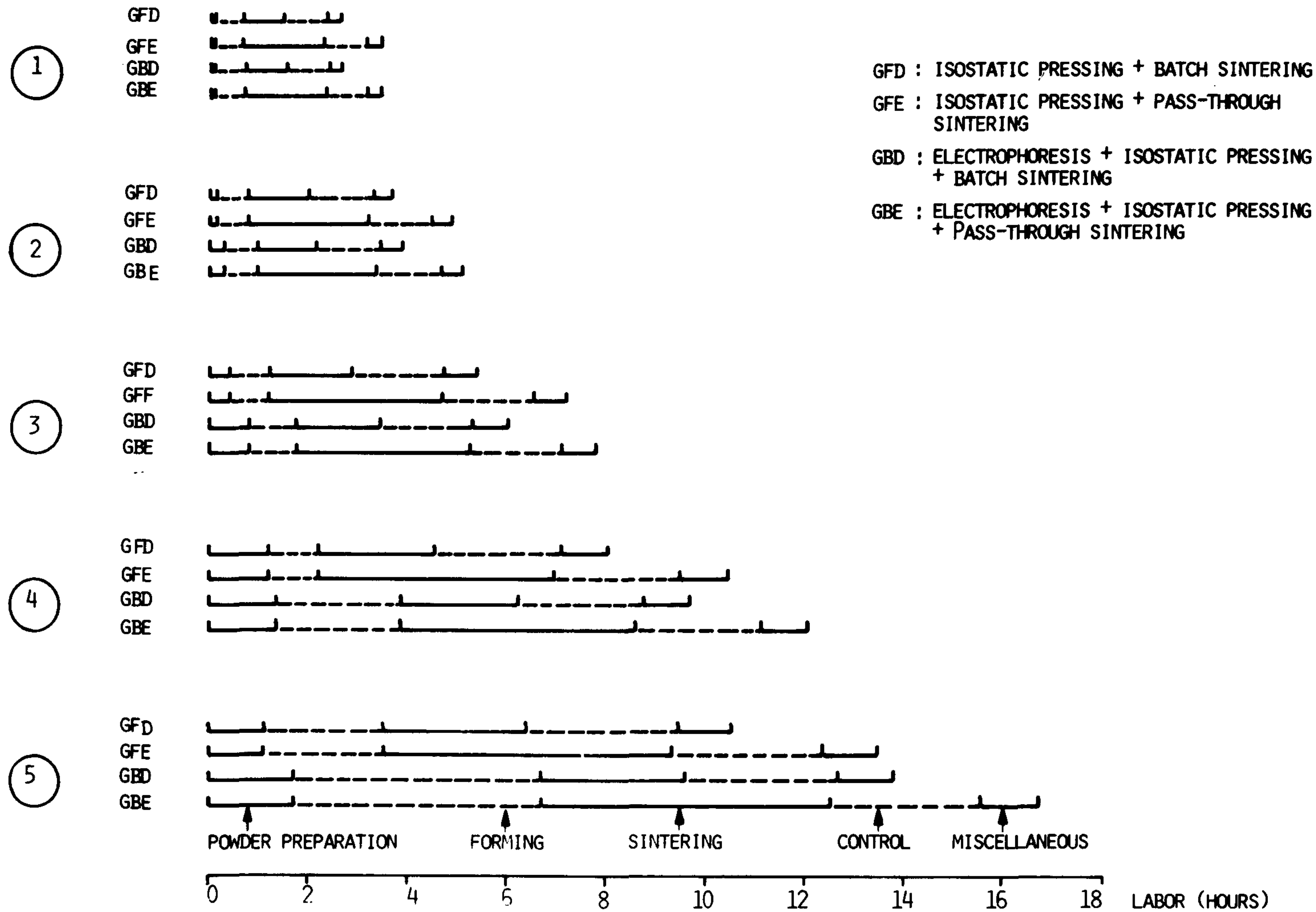

Figure B-1 - Labor for each Step of Different Manufacturing Routes and Different Tube Dimensions

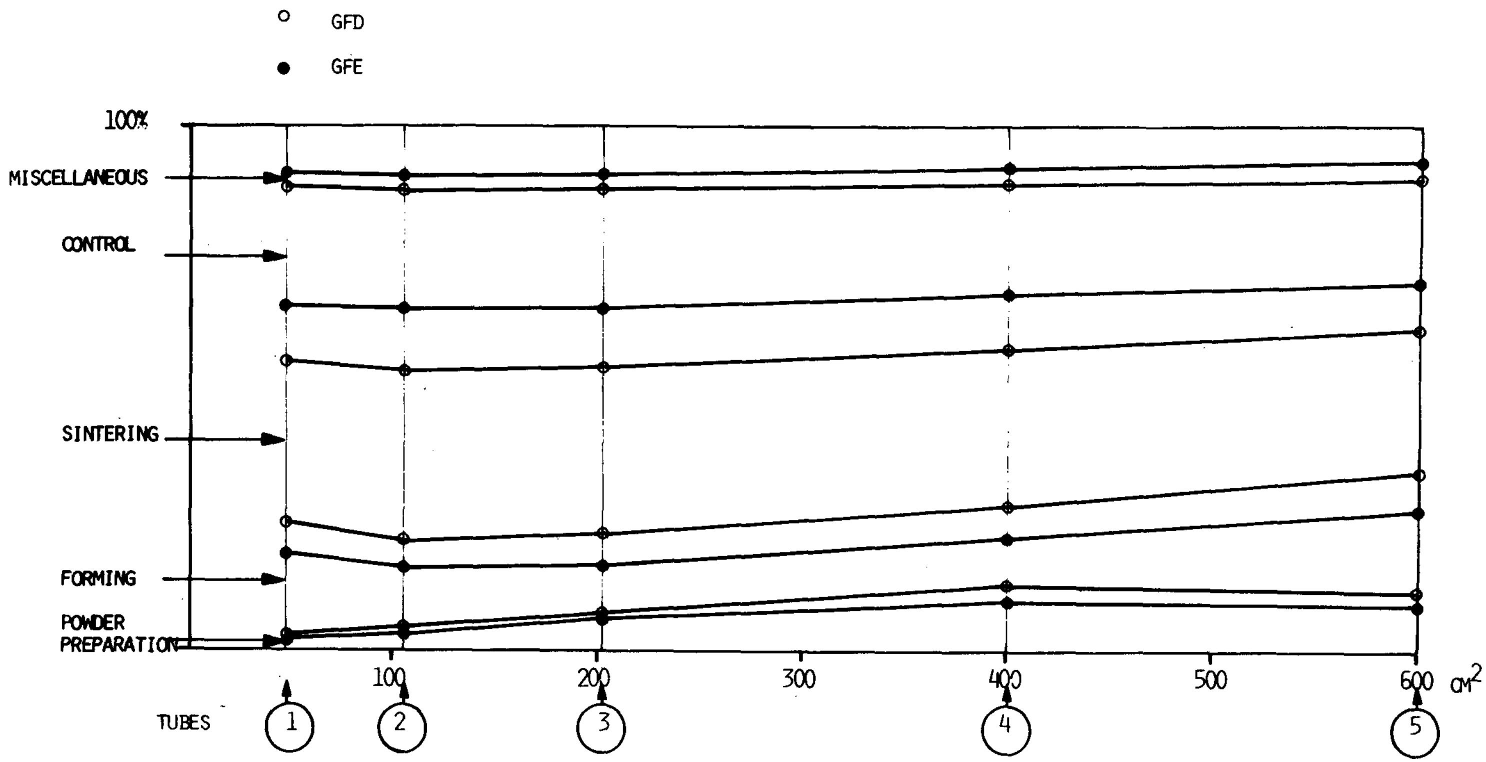

Figure B-2 - Relative Labor for each Step of GFD and GFE Routes

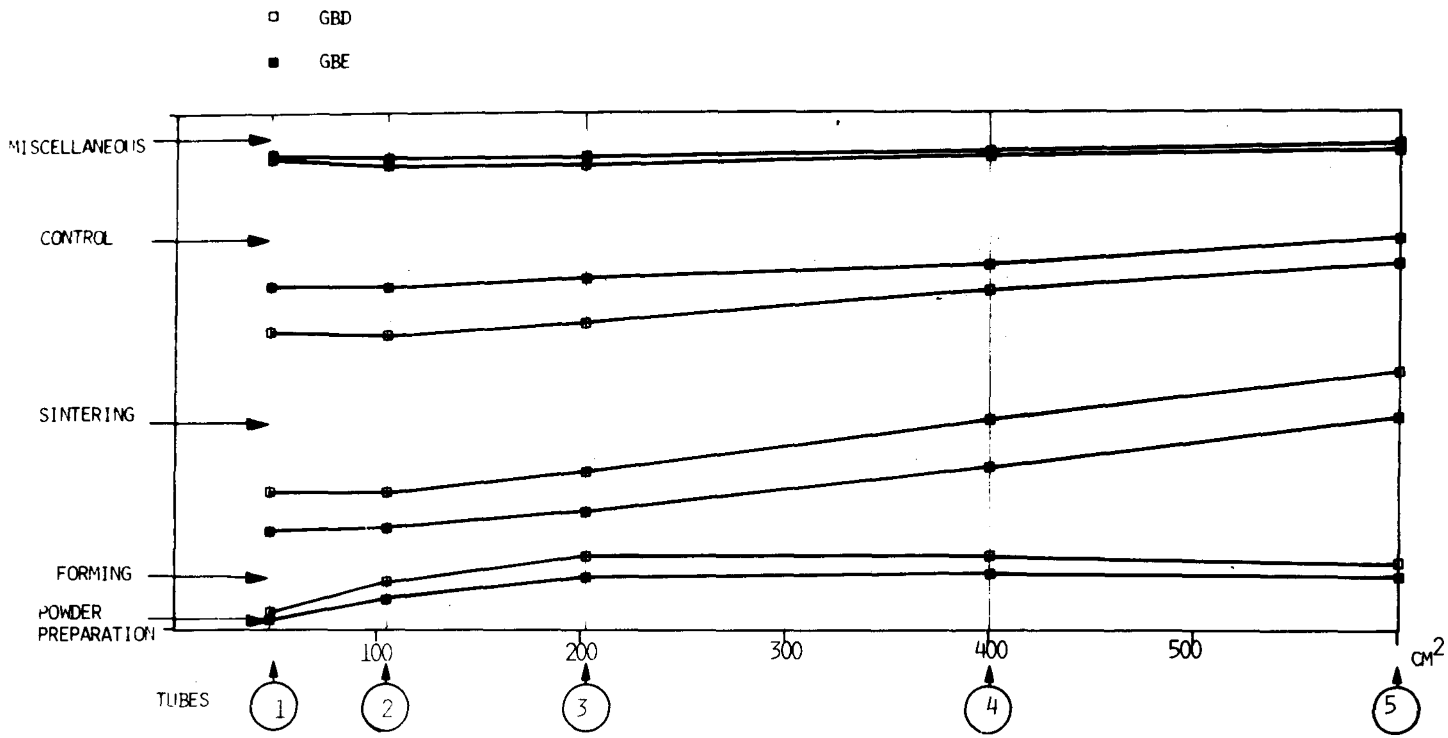

Figure B-3 - Relative Labor for each Step of GBD and GBE Routes

Materials

The costs of raw materials and other materials (solvent for electrophoresis, concrete for batch sintering) used for the fabrication of 100 tubes are given in Table B-12 (at 100 % yield).

Table B-12

Cost of Raw Materials and Purchased Components by Route and Dimensions (in dollars)

Route	Tube 1	Tube 2	Tube 3	Tube 4	Tube 5
GFD	41.44	62.61	103.49	187.44	351.29
GFE	45.10	97.73	189.96	363.54	568.85
GBD	41.16	62.00	101.85	182.52	341.49
GBE	44.82	97.12	188.32	358.61	559.05

Product yields

The factory cost is calculated according to the Arthur D. Little guidelines ; however, the overall product yield takes into account the tube size and, thus, fabrication difficulties. This contrasts with the guidelines which assumed a yield of 75 % for all cases. No allowance is made for the route considered. The projected yields are given in Table B.13.

Table B-13

Product Yield by Tube Dimensions

Tube	Yield
1	0.90
2	0.85
3	0.80
4	0.70
5	0.60

Factory cost assessment

The equipment costs and work areas have been determined using the results of Part A. A breakdown of the factory cost for 100 tubes to the nearest dollar is given in Table B-14. Allowance is made for the yields shown above.

B - 9 SELLING PRICE ASSESSMENT

The selling price for 100 β"-alumina tubes is given in Table B-15. The selling price per 100 cm^2 of active area is given in Figure B-4 by tube dimensions. It should be noted that the price calculated in Part A for a 330-cm^2 active area β"-alumina tube fabricated by route H11 J1 M1, which is similar to route GFD, is in line with these results. The lowest prices are for those tubes with active area ranging from 200 to 400 cm^2 produced by the routes using batch sintering. These results will be discussed in Part C.

Table B-15
Selling Prices ($) of 100 β"-alumina Tubes by Route

Route	Tube 1	Tube 2	Tube 3	Tube 4	Tube 5
GFD	210	322	527	991	1,867
GFE	274	494	892	1,742	2,994
GBD	201	319	539	1,050	2,012
GBE	271	495	902	1,810	3,165

Table B-14

Factory Cost For $\beta''-Al_2O_3$ Tubes by Size and Production Route (100 Tubes-$ 1980)

	Route	Labor	Materials and Purchased Components	Overhead on labor	Overhead on materials	Equipment depreciation	Rent	Factory cost
Tube 1	GFD	29	46	44	5	15	3	142
	GFE	38	50	57	5	22	3	175
	GBD	30	46	44	5	13	3	141
	GBE	39	50	58	5	21	3	176
Tube 2	GFD	43	74	65	7	23	4	216
	GFE	58	115	86	11	40	5	315
	GBD	46	73	67	7	21	4	218
	GBE	60	115	90	11	39	6	321
Tube 3	GFD	68	129	101	13	37	7	355
	GFE	90	237	134	24	73	9	567
	GBD	75	127	113	13	36	8	372
	GBE	97	235	146	24	71	10	583
Tube 4	GFD	115	268	172	27	71	13	666
	GFE	149	519	224	52	143	19	1,106
	GBD	139	261	208	26	71	15	720
	GBE	173	512	260	51	145	21	1,162
Tube 5	GFD	176	585	264	59	134	24	1,242
	GFE	225	948	337	95	250	32	1,887
	GBD	230	569	345	57	139	29	1,369
	GBE	278	932	417	93	258	38	2,016

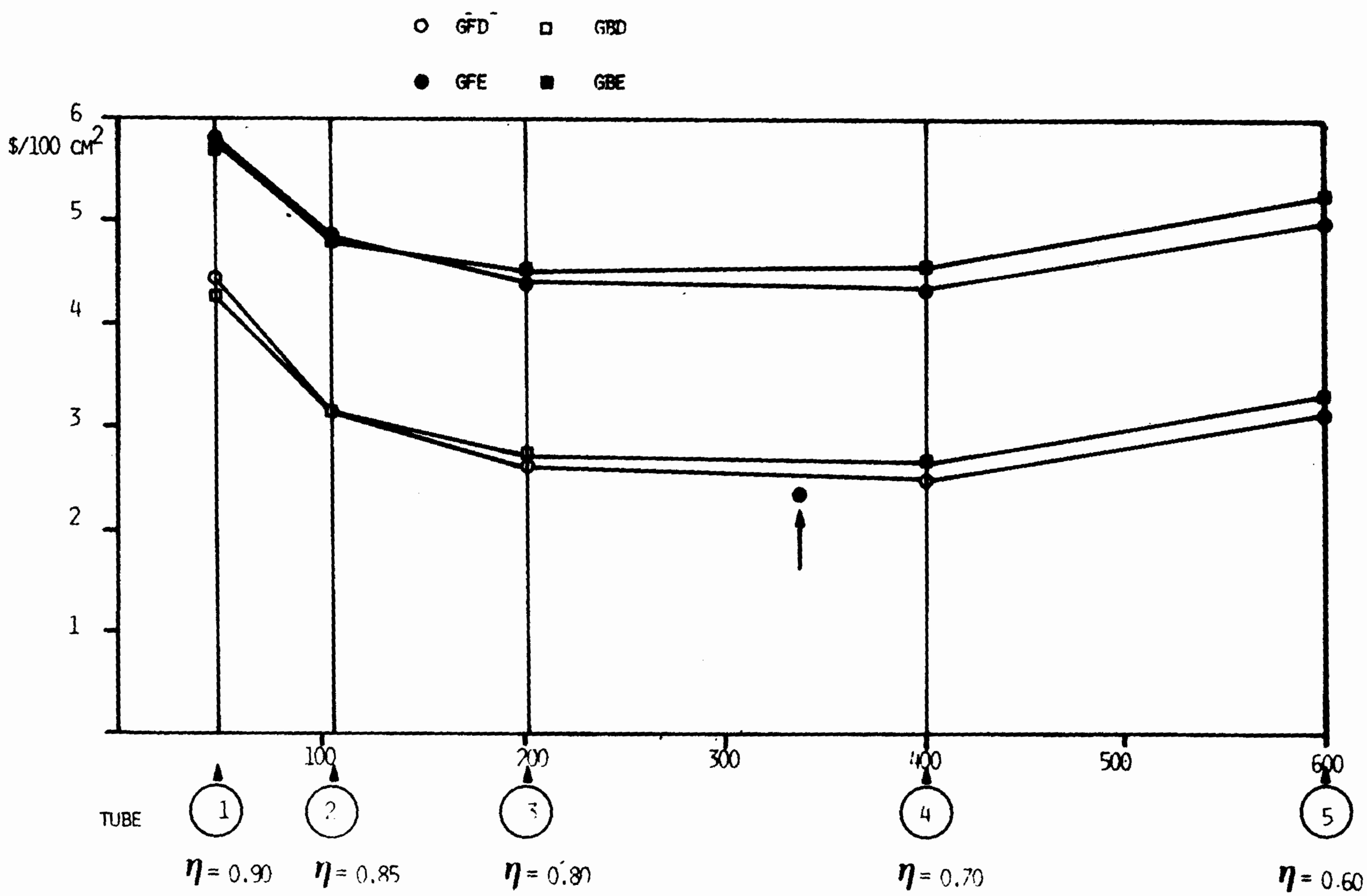

Figure B-4 - Selling Prices of β''-Al_2O_3 by Active Area

Part C

COMPARISON

CONTENTS

ILLUSTRATIONS

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COMPARISON

C - 1 GENERAL

This study followed directly from RP726-1, which was a technico-economic evaluation of the sodium-sulfur battery off-peak storage unit described in Table C-1. In RP726-1, the unit cell was a sodium-sulfur β-alumina system. This study similarly evaluated the same storage battery unit based on unit cells with β"-alumina tubes.

Table C-1
Sodium-Sulfur Storage System Specifications

Lifetime	10 years or 2,500 cycles
Energy Efficiency	75 % (not including power conditioning equipment)
Utilization cycle	10-hour discharge 7-hour charge
Recoverable Energy stored	100 MWh
Voltage at end of charge	1 000 V

In the present study, we developed 1980 prices for raw materials, labor, and other costs according to the Revised Guidelines for Estimating the Capital Costs of Advanced Battery Systems for Utility Energy Storage, RP1198-2, Interim-Report, September 1979, by James H.B. George.

First, we completed a new cost estimate for 100-MWh unit with β-alumina tubes, to obtain the 1980 prices. Technical assumptions were the same as in the 1976 study, except for the β-alumina tube production, which has been reconsidered (see § A - 2.1, below).

Second, we made a complete cost estimate for a 100-MWh unit with cells of the same size as in the proceeding study, but using β"-alumina instead of β-alumina.

Third, we optimized the β"-alumina cell for minimum cost and made a final cost estimate for a 100-MWh unit.

Thus, it is possible to compare the 1980 prices for batteries containing the :

- Optimal size β-alumina cell
- The same size cell using β"-alumina
- Optimal size β"-alumina cell

The methodology for those technico-economic evaluations can be found in EPRI Report EM-413, the final report of RP726-1.

C - 2 COMPARISON BETWEEN β- AND β"-ALUMINA TUBES

C - 2.1 Assessment of the selling price of the β-alumina tubes

Adjusting the 1976 selling price only for inflation results in prices that do not reflect the state of the art. In addition, the 1976 prices did not include quality control in the factory cost. Therefore, we decided to reassess the selling price by tube size and fabrication route (already presented in Table B-1). The product yields applied are those determined for β"-alumina in Table B-13. A breakdown of the factory cost for 100 tubes, assuming the yields given in Table B-13, is given in Table C-2. The selling price for 100 tubes is given in Table C-3.

Table C-2

Factory Cost For β-Al_2O_3 Tubes by Size and Production Route (100 Tubes - $ 1980)

	Route	Labor	Materials and purchased components	Overhead on labor	Overhead on materials	Equipment depreciation	Rent	Factory cost
Tube 1	GFD	26	46	39	5	13	2	131
	GFE	35	50	52	5	20	3	165
	GBD	26	46	39	5	12	3	131
	GBE	35	50	53	5	19	3	165
Tube 2	GFD	38	73	57	7	20	4	199
	GFE	52	114	78	11	36	5	296
	GBD	41	72	61	7	19	4	204
	GBE	55	114	82	11	35	5	302
Tube 3	GFD	60	127	89	13	34	6	329
	GFE	82	235	122	23	66	9	537
	GBD	67	125	101	12	32	7	344
	GBE	89	233	134	23	64	10	553
Tube 4	GFD	102	259	152	26	64	12	615
	GFE	136	511	204	51	129	18	1,049
	GBD	125	254	188	25	64	14	670
	GBE	160	506	240	51	131	20	1,108
Tube 5	GFD	158	566	237	57	121	23	1,162
	GFE	207	929	310	93	226	31	1,796
	GBD	212	554	318	55	125	28	1,292
	GBE	260	917	390	92	233	36	1,928

Table C-3

Selling Prices (1980 $) of 100 β-Alumina Tubes by Size and Production Route

Route	Tube 1	Tube 2	Tube 3	Tube 4	Tube 5
GFD	192	294	485	910	1,721
GFE	255	460	831	1,627	2,803
GBD	186	293	497	972	1,877
GBE	251	460	844	1,697	2,975

C - 2.2 Comparison of 1976 and 1980 selling prices for β-alumina

The selling price comparison is presented in Table C-4. Prices have been adjusted for inflation by 10 % per year, and the 1980 prices include increased technical sophistication and awareness. The inclusion of quality control costs in the factory cost and the more precise estimate allowed by improved technical knowledge have led to a considerable increase in selling prices. In addition, in 1976, labor, materials, and purchased components had been underestimated for the routes using pass-through sintering.

Table C-4

1980 to 1976 Selling Price Ratios for β-Alumina Tubes After Technical and Economical Readjustements of 1976 Costs

Route	Tube 1	Tube 2	Tube 3	Tube 4	Tube 5
GFD	2.34	2.41	2.33	1.86	1.78
GFE	3.54	4.74	5.23	4.58	3.90
GBD	1.96	2.20	2.39	2.23	2.35
GBE	2.95	4.26	5.31	5.64	5.34

C - 2.3 Comparison of β- and β"-alumina selling prices

This comparison is presented in Table C-5 by tube size and production route. The β"-alumina selling price is slightly higher than that of β-alumina. This is mainly due to the need to store the tube in a moisture-free atmosphere after sintering until packing, and to supervise sintering more closely. These requirements offset the benefit of a lowered sintering temperature.

Table C-5
Selling Price Ratio of β"-Alumina Tubes to β-Alumina Tubes

Route	Tube 1	Tube 2	Tube 3	Tube 4	Tube 5
GFD	1.09	1.09	1.09	1.09	1.08
GFE	1.07	1.07	1.07	1.07	1.07
GBD	1.08	1.09	1.08	1.08	1.07
GBE	1.08	1.08	1.07	1.07	1.06

C - 3 SIZE OPTIMIZATION FOR β"-ALUMINA CELLS

The cost in 1980 dollars/Kwh has been computed as a function of cathode thickness and tube diameter (see Figure C-1). The optimal diameter of the β"-alumina was found identical to the diameter of the β-alumina tube previously discussed (26-mm immer diameter ; 29-mm outer diameter). But the β"-alumina tube allows a thicker sulfur electrode and a smaller cycling range, with Na_2S_5 (as opposed to Na_2S_3) being the ultimate discharge product.

It should also be noted that, in the case of β"-alumina, with a thick electrode almost exclusively cycling to Na_2S_5, the difference of cell price does not justify obtaining 80 % efficiency instead of 75 % (see Figure C-1). However, with cells designed for 80 % efficiency, it is no longer necessary to use a power recovery system in the unit. This simplification of the β"-alumina results in cost savings. As a result, the β"-alumina cell was optimized for 80 % efficiency instead of 75 %.

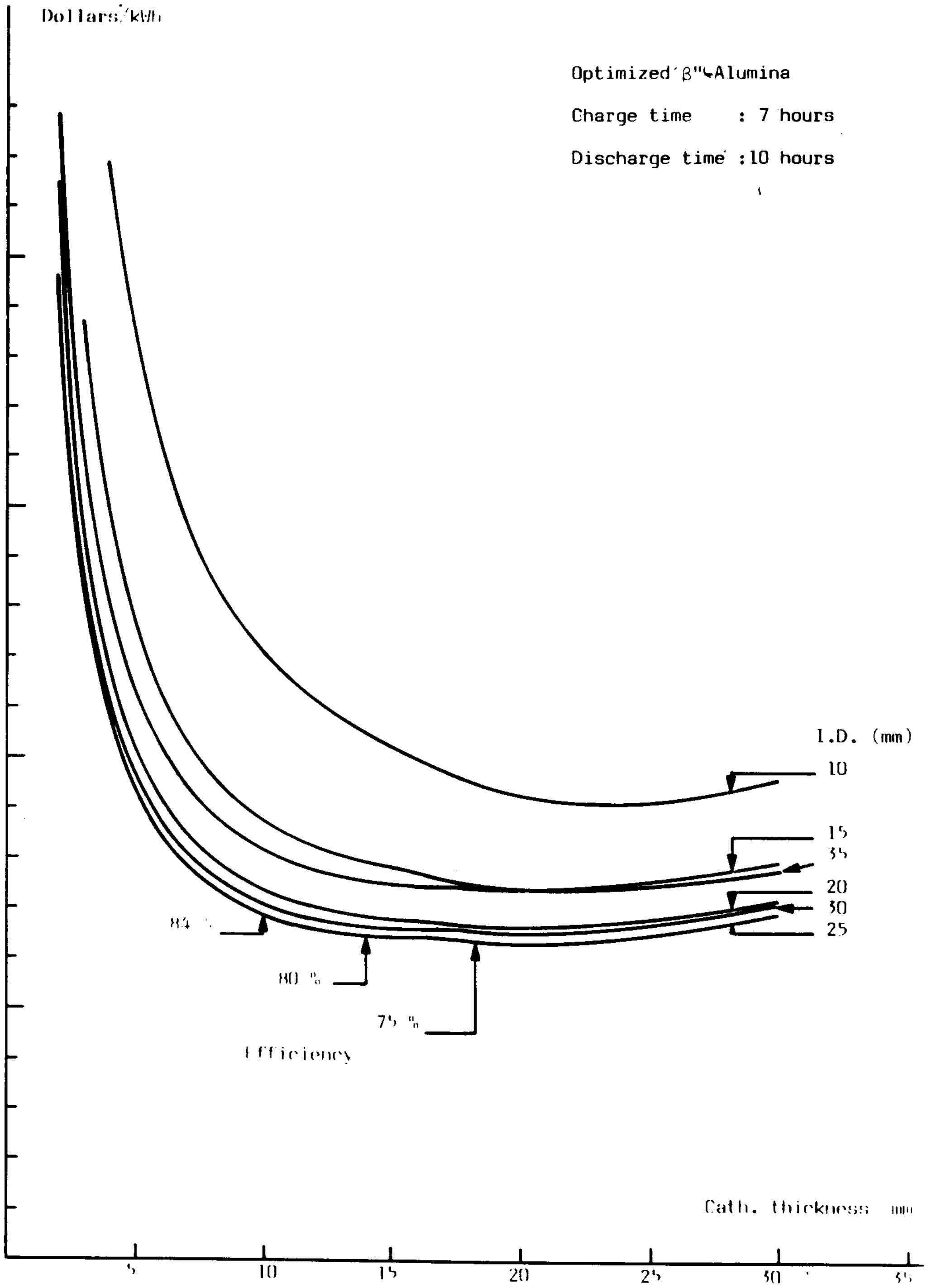

Figure C-1 - Economics of the β"-Alumina Cell

C - 4 TECHNICAL COMPARISON BETWEEN β- AND β"-ALUMINA CELLS

The following tables (C-6, C-7, C-8, and C-9) give a comparison between three types of cells :

- Optimized β-alumina cell (cell chosen in 1976 study)
- Nonoptimized cell with β"-alumina (same dimensions as the preceding β-alumina cell)
- Optimized β"-alumina cell

The sulfur electrode of the nonoptimized β"-alumina cell is identical to the sulfur electrode of the β -alumina cell. In both cases charge and discharge ends are set to produce the same sulfur electrode use.

Table C-6
Cell Geometrical Characteristics

Detailed characteristics of cell	β-Alumina		β"-Alumina Nonoptimized	β"-Alumina Optimized
Interior diameter of β-alumina	26.1	mm	26.1	26.1
Exterior diameter of β-alumina	29	mm	29	29
Tube thickness	1.45	mm	1.45	1.45
Length of straight part of β-alumina	434	mm	434	434
Cathode compartment thickness	10	mm	10	14
α-alumina axial thickness	3.7	mm	3.7	4.2
Aluminium container thickness	1	mm	1	1
Steel container thickness	0.5	mm	0.5	0.5
Exterior diameter (α-alumina)	56	mm	56	64
Total cell height	596	mm	596	592
β-alumina area	409.5	cm^2	409.5	409.5
Total overall cell volume	1.469	dm^3	1.469	1.906

Table C-7
Cell Weight Characteristics

		β"-alumina	
	β-Alumina	Nonoptimized	Optimized
Sulfur weight	691 g	691 g	1,072 g
Sodium weight	420 g	420 g	477 g
β-alumina weight	180 g	180 g	180 g
Steel container weight	303 g	303 g	356 g
Aluminium container weight	63 g	63 g	69 g
Carbon felt weight	57 g	57 g	89 g
α-alumina weight	21 g	21 g	34 g
Total weight	1,735 g	1,735 g	2,278 g

Table C-8
Cell Electrical Characteristics

	β-Alumina	β"-Alumina Nonoptimized*	β"-Alumina Optimized
Charge time	7 h	7 h	7 h
Discharge time	10 h	10 h	10 h
Cycling depth (limiting degree of charge)	62.6 %	62.6 %	51.4 %
End of charge limit (molesNa/moles S)	0.284	0.284	0.361
End of discharge limit (moles Na/ moles S)	0.701	0.701	0.704
Charge current density	84.5 mA/cm^2	84.5 mA/cm^2	107.6 mA/cm^2
Discharge current density	59.1 mA/cm^2	59.1 mA/cm^2	75.4 mA/cm^2
IR drop in β-alumina on charge	202 mV	65 mV	83 mV
IR drop in β-alumina on discharge	141 mV	46 mV	58 mV
Mean charge voltage (single-phase region)	2.16 V	2.028 V	2.087 V
Mean charge voltage (two-phase region)	2.48 V	2.351 V	2.292 V
Mean discharge voltage (single-phase region)	1.63 V	1.724 V	1.672 V
Mean discharge voltage (two-phase region)	1.83 V	1.927 V	1.877 V
Short circuit current	200 A	340 A	310 A
Maximum capacity on discharge	242 Ah	242 Ah	309 Ah
Maximum energy stored	408 Wh	431 Wh	523 Wh
Charge-discharge energy efficiency	74.7 %	84.1 %	80.3 %

*In the case of nonoptimized β"-alumina type of cell, the sulfur electrode is identical to the sulfur electrode of the "β-alumina type". The ends of charge and discharge are chosen so as to correspond to the same sulfur electrode polarizations, in both cases.

Table C-9

Cell Thermal Characteristics

	β-Alumina	β"-Alumina Nonoptimized	β"-Alumina Optimized
Mean operating temperature	350° C	350° C	350° C
Mean heat evolution on charge (single-phase region)	7.0 W	2.3 W	5.6 W
Mean heat evolution on charge (two-phase region)	11.2 W	6.4 W	5.6 W
Mean heat evolution on discharge (single-phase region)	8.3 W	6 W	9.1 W
Mean heat evolution on discharge (two-phase region)	8.3 W	6 W	9.1 W
Mean heat evolution for the complete cycle	8.23 W	4.92 W	7.67 W
Maximum rate of temperature rise (with no external cooling, cell at 350° C)	0.37° C/mn	0.21° C/mn	0.23° C/mn
Thermal capacity of cell	1,830 J/°C	1,830 J/°C	2,420 J/°C

C - 5 COST COMPARISON BETWEEN β- AND β"-ALUMINA CELLS

Principal raw material purchasing prices are given in Table C-10. A cost comparison between β- and β"-alumina tubes is given in Table C-11 for electrolyte tubes of 26-mm inner diameter, 29-mm outer diameter, and 434 mm long. Costs make allowance for the production yields discussed in § B - 2.8 (Table B-13). The production yield for fabrication, filling, inspection, and final test of complete cells was chosen as 95 % according to the Arthur D. Little guidelines. Factory cost comparisons between β- and β"-alumina types of cells are given in Table C-12 and C-13.

Table C-10

Raw Material Purchase Prices ($/kg)

Sodium	1.84
Sulfur	0.3
α-alumina powder	1.10
Carbon mat	35.6
Aluminium (ingot)	4
C12 Steel (ingot)	0.58
Glass	4.3
Chromium	10.5

Table C-11

Factory Cost Comparison Between
β and β"-Alumina Tubes

	β-Alumina	β"-Alumina
Labor	1.123	1.253
Material and purchased components	2.678	2.790
Overhead on labor	1.684	1.880
Overhead on materials	0.268	0.279
Equipment depreciation	0.66	0.75
Rent	0.123	0.135
Factory cost ($)	6.536	7.087

Table C-12

Cell Factory Cost Comparison - by Components

Labor cost + materials cost + Overhead on labor and materials	β-Alumina cell	Nonoptimized β"-alumina cell	Optimized β"-alumina cell
α-alumina	0.267	0.267	0.343
Glass seal	0.260	0.260	0.261
Sodium and filling	1.034	1.034	1.163
Sulfur and filling	0.382	0.382	0.523
Graphite and electrode fabrication	2.463	2.520	3.822
Steel container + chrome plating	1.489	1.489	1.689
Aluminium container	0.336	0.336	0.367
Thermo-compression	0.438	0.511	0.511
Quality control and tests	0.540	0.581	0.589
Others	0.175	0.177	0.212
Total ($)	7.384	7.557	9.48
Equipment depreciation	0.57	0.58	0.73
Rental cost	0.57	0.58	0.73
Factory cost for cell assembly and tests	8.52	8.72	10.9
Factory cost of β or β"-alumina	6.863	7.44	7.44
Cell factory cost ($)	15.38	16.16	18.3
Cell factory cost ($/kWh)	37.7	37.5	35.0

Table C-13

Cell Factory Cost Comparison
By Financial Category

	β-Alumina cell	Nonoptimized β"-alumina cell	Optimized β"-alumina cell
Labor	2.133	2.338	2.375
Materials	7.358	7.476	9.137
Overhead on labor	3.199	3.506	3.562
Overhead on materials	0.736	0.748	0.914
Equipment depreciation	1.263	1.367	1.516
Rental cost	0.699	0.722	0.859
Cell factory cost ($)	15.38	16.16	18.33
Cell factory cost($/kWh)	37.7	37.5	35.0

Shifting from β- to β"-alumina increases the cell cost by 5 % or 19 %, depending on whether the cell size is optimized for β"-alumina. However, the useful energy content is greater by 6 % in the nonoptimized cell and by 28 % in the optimized cell, partially offsetting the higher cost of the optimized β"-alumina cell. But the main advantage of the shift to β"-alumina is increased efficiency. This can only be used to full advantage in a more efficient module arrangement, which results in a less costly design for the complete 100-MWh unit. Table C-14 shows the theoretical number of cells required and, because of the lower cell potential for recharge, changes in the series-parallel number of connections.

Table C-14

100-MWh Unit Configuration

	β-Alumina	β"-Alumina Nonoptimized	β"-Alumina Optimized
Useful energy per cell (Wh)	408	431	523
Total number of cells (theoretical)	245,000	232,000	191,200
Cell mean charge voltage (phase 1)	2,165 V	2,028 V	2,087 V
Unit mean charge voltage (phase 1)	866 V	862 V	910 V
Cell mean charge voltage (phase 2)	2,448 V	2,351 V	2,292 V
Unit mean charge voltage (phase 2)	1,000 V	1,000 V	1,000 V
Total series connections	400	425	436
Number of strings	5	5	5
Number of modules	2,000	2,125	2,180
Theoretical number of cells per module	123	109	88

C - 6 RELIABILITY STUDY

The reliability study for β-alumina was made assuming a cell reliability of 0.95. In the case of β"-alumina, we assumed cell reliabilities of 0.95 and 0.90 (see Figure C-2).

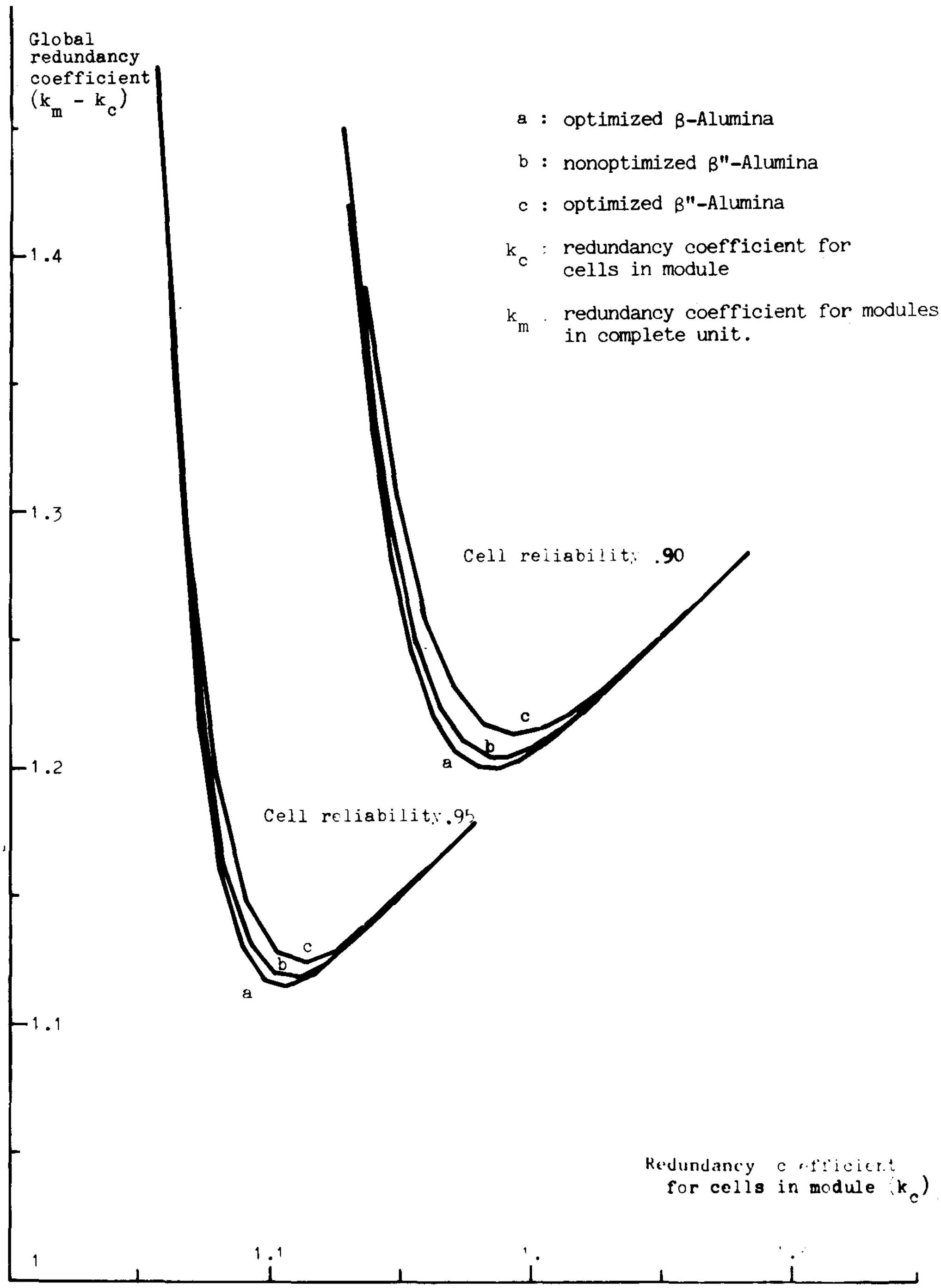

Figure C-2 - Redundancy Optimization

We obtained the corresponding optimal global redundancy coefficients shown in Table C-15.

Table C-15
Reliability Comparison

	Optimized β-alumina	Nonoptimized β"-alumina		Optimized β"-alumina	
Cell reliability	0.95	0.95	0.90	0.95	0.90
Global redundancy	1.115	1.119	1.205	1.125	1.213
Cell factory cost ($)	15.38	16.16	16.16	18.33	18.33
Cell energy (Wh)	408	431	431	523	523
Cell cost($ /kWh)	42.03	41.96	45.18	39.43	42.51

This clearly shows that β"-alumina will only be interesting in comparison with β if its reliability is the same. If β"-alumina reliability is lower than β-alumina reliability, β-alumina will be better from an economic point of view. As a result, for the present study, we assume the same reliability for cells containing β- and β"-alumina. Table C-16 gives the corresponding optimal results of cells and module redundancy studies.

β"-alumina cell reliability must be the same as β-alumina cell reliability. If not, shifting from β- to β"-alumina would be disadvantageous.

Table C-16

Results of Reliability Study

	β-Alumina	β"-Alumina Nonoptimized	β"-Alumina Optimized
Assumed cell reliability	0.95	0.95*	0.95*
Number of supplementary cells/module	13	12	10
Number of supplementary module/battery	17	17	22
Overall increase for reliability purpose	11.5 %	11.9 %	12.5 %

*β"-alumina cell reliability has to be the same than β cell reliability. If not, shifting from β to β"-alumina would be a drawback.

C - 7 MODULE STUDY AND OPTIMIZATION

For module optimization, the following factors were taken into account :

- Extra cells are incorporated to provide redundancy in case of failure during useful battery life.
- Capacity and power losses occur when a large number of cells are connected in parallel. Those losses are correlated with the size, weight, and cost of the different connecters and busbars.
- Nitrogen circulation is used for heating as well as cooling.
- The thickness of the insulation is minimal and will protect a hot module exposed to ambiant air for only up to one hour during transport or maintenance.

Table C - 17 lists the parameters of the cell arrangement in the modules, the main characteristics of the busbars, and those calculated for the insulating jacket.

Table C-17

Module Parameters

	β-Alumina	β"-Alumina Nonoptimized	β"-Alumina Optimized
Theoretical number of cells required	123	109	88
Supplement corresponding to parallel connections	8	7	6
Supplement corresponding to failures in lifetime	13	12	10
Total	144	128	104
Number of submodules	4	4	4
Number of cells per submodule	36	32	26
Number of ranks	6	4	4
Number of cells per rank	6	8	7
Loss in efficiency due to connections	2 %	2.1 %	2 %
Loss in useful capacity due to connections	5.4 %	6.4 %	6.6 %
Cell supplement required to cover capacity loss (included in above)	8	7	6
Ratio of aluminium busbars to cell weight	0.11	0.11	0.14
Cross-section of busbars in rank	5.5 cm^2	7.1 cm^2	9 cm^2
Cross-section of busbars in submodule	30 cm^2	26 cm^2	33 cm^2
Cross-section of busbars in module	120 cm^2	105 cm^2	133 cm^2
Concrete jacket thickness	4.2 cm	4.2 cm	4.1 cm
Weight of cells	250 kg	222 kg	237 kg
Weight of busbars	28 kg	24 kg	32 kg
Weight of concret jacket	228 kg	203 kg	210 kg
Total module weight	506 kg	449 kg	479 kg

C - 8 COST COMPARISON BETWEEN β AND β"-ALUMINA MODULES

The mains raw material costs are assumed as follows :

- Aluminium (busbars) 1.83 \$/kg
- Concrete 23.2 \$/metric T
- Insulator (vermiculite) 68.3 $\$/m^3$

Module price not only includes the module itself (cells, internal busbars, insulating layer, and cover) but also the components assigned to each module (outer module cover plate, gas flow connection piping, intermodule busbars, and insulator). Table C-18 and C-19 present comparisons of factory cost between modules made of β- and β"-alumina cells.

The factory costs of the modules for a 100-MWh battery, including the supplementary modules required for 10 years of operation are :

- M \$ 5.12 with β-alumina (optimized)
- M \$ 5.25 with β"-alumina (nonoptimized)
- M \$ 4.89 with β"-alumina (optimized)

Thus, shifting from β- to β"-alumina with appropriate optimization of the cathode will decrease the factory cost by 5 %. Those figures do not include civil and structural cooling and heating facilities, which are discussed below.

Table C-18

Module Factory Cost Comparison - by Components

	β-Alumina	β"-Alumina Nonoptimized	β"-Alumina Optimized
Materials costs (cells not included)			
Busbars (internal)	51.24	43.92	58.56
Concrete (jacket and cover)	5.29	3.97	4.87
Concrete (outer module cover plate)	1.45	1.00	1.29
Concrete (gas flow connection piping)	0.64	0.77	0.87
Intermodule busbar	42.09	36.79	46.72
Insulator	68.3	50.0	53.75
Total ($)	169	136.5	166
Labor (cells not included)			
Rank busbars	1.36	1.21	1.06
Terminal busbars	0.67	0.67	0.67
Rank busbars weld	2.38	1.59	1.59
Terminal busbars weld	0.91	0.91	0.91
Concrete mixing	0.63	0.47	0.58
Concrete casting	5.55	5.35	5.50
Connecting busbar	1.52	1.52	1.52
Assembly	2.54	2.54	2.54
Quality control	0.67	0.67	0.67
Total ($)	16.23	14.93	15.04
Overhead on materials	16.9	13.66	16.6
Overhead on labor	24.34	22.42	22.56
Rental costs	78	73	71
Equipment depreciation	20	17	19
Module factory cost	324.5	277.5	310.2
Cells	2,214.7	2,068.5	1,906.3
Total module factory cost ($)	2,540	2,340	2,220

Table C-19

Module Factory Costs Comparison - by Financial Category

	β-Alumina	β"-Alumina Nonoptimized	β"-Alumina Optimized
Material costs	1,228.5	1,093.4	1,116.2
Labor	323.4	314.2	262.0
Overhead on materials	122.8	109.3	111.6
Overhead on labor	485.1	471.3	393.1
Rental costs	178.7	161.3	161.5
Equipment depreciation	202	192	177
Module factory cost ($)	2,540	2,340	2,220
Nominal energy	50 kWh	47.06 kWh	45.87 kWh
Module factory cost ($/kWh)	50.8	49.7	48.4

C - 9 100-MWh STORAGE BATTERY UNIT LOCATION

The battery system consists of 5 strings or "super modules" each of 20 MWh, arranged in parallel. Each string contains either 400 modules in series (β-alumina), 425 modules in series (β"-alumina nonoptimized), or 436 modules in series (β"-alumina optimized).

The system has been designed taking into account the thermal insulation required in addition to the nitrogen coolant circulation. To avoid excessive energy consumption for coolant circulation, the nitrogen channels, which surround the modules (except for the upper portions) and are constructed in refractory concrete, must have a large cross-section. The whole system, consisting of cooling channels and modules, is thermally insulated by a layer of foamed concrete. On the top, the insulation covering the modules is protected by a concrete cover which sheds rainwater into side drain channels. The earth excavated during construction is piled on the sides to serve as additional thermal insulation.

The circulation system is located at the far end of the unit in a block containing both the cooling and start-up system. The front of the unit is a one-story building of light construction containing the switchgear that connects the strings in parrallel, the power conditioning equipment, and the control system. The insulation has been designed so that with the system completely shut down, cooldown from 330 to 290° C takes when the ambient temperature is 20° C.

Each of the five strings contains an independent nitrogen circulation system. This allows shutdown of individual subunits for maintenance when a module breaks down, so that 80 % of the unit capacity is always available. The nitrogen circulates through parallel channels. While this arrangement occupies a great deal of space, it allows the use of a lower pumping energy since pressure drops are smaller. In addition, a single module can be disconnected without cutting nitrogen circulation elsewhere. The nitrogen circulation removes the heat generated on charge and discharge and is also used to heat up the system on initial start-up using heat exchangers. These heat exchangers are not located in the primary nitrogen cooling circuit ; such an arrangement would involve a high pressure drop, and an excessive power requirement. Instead, a secondary loop has been incorporated for start-up, with a mass flow of about 20 % of that in the primary circuit. The distribution of the coolant between individual cells has been studied, and variations in distribution have been compensated for by increasing the flow over the theoretical requirement, so that the cells least exposed to coolant still receive the required flow (see Tables C-20, and C-21).

Table C-20
Nitrogen Flow Data

	β-Alumina	β"-Alumina Nonoptimized	β"-Alumina Optimized
Theoretical nitrogen flow (350° C)	16.6 m^3/s	12.5 m^3/s	12.5 m^3/s
Practical flow	47.6 m^3/s	33.6 m^3/s	30.8 m^3/s
Recycled flow (10 %)	4.8 m^3/s	3.4 m^3/s	3.1 m^3/s
Heat exchanger circuit	10.8 m^3/s	10.8 m^3/s	10.8 m^3/s
Total flow and fans	64 m^3/s	48 m^3/s	45 m^3/s

Table C-21
Pressure Drop Data

	β-Alumina	β"-Alumina Nonoptimized	β"-Alumina Optimized
Module	519 N/m^2	276 N/m^2	263 N/m^2
Distribution	102 N/m^2	52 N/m^2	43 N/m^2
Nitrogen circuit	191 N/m^2	95 N/m^2	80 N/m^2
Total	812 N/m^2	423 N/m^2	386 N/m^2
+ Friction losses	187 N/m^2	132 N/m^2	121 N/m^2
Total rounded off	1 000 N/m^2 (10 g/cm^2)	555 N/m^2 (5.6 g/cm^2)	507 N/m^2 (5.1 g/cm^2)
Theoretical fan power	64 kW	26.6 kW	22.8 kW
Pratical fan power	94 kW	39.1 kW	33.5 kW
Total electric power requirement	470 kW	200 kW	170 kW

The efficiency of the β-alumina cells was 75 %. To provide electric power for accessory service, it was necessary to recover thermal energy. This energy could be used to operate the nitrogen flow system, which would otherwise involve a reduction of about 8 % in overall system efficiency. This may be carried out using a steam circuit at 270° C, 56 atm. incorporating a turbogenerator. Figure C-3 shows the complete nitrogen system required for a β-alumina type of battery.

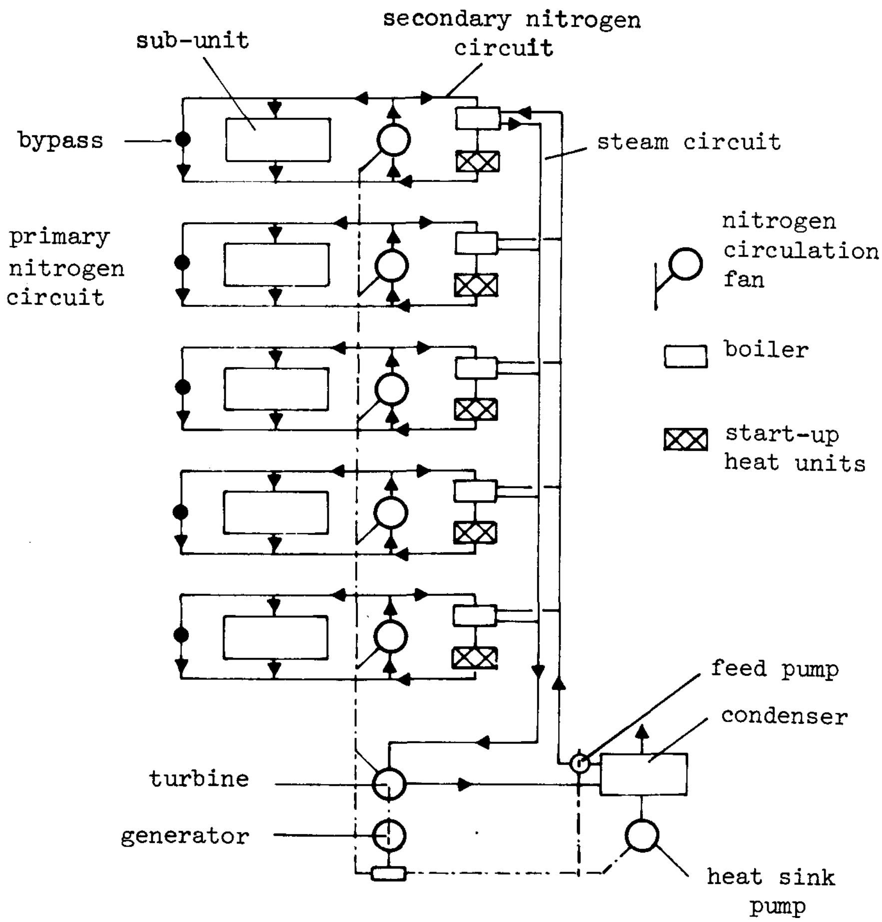

Figure C-3 - Schematic Diagram of Nitrogen Cooling and Preheating Systems (β-type Battery)

With β"-alumina cells, an efficiency of 80 % was obtained at sufficiently low cost, to permit simplifying the nitrogen system : 5 % of the electrical energy (6.66 MWh per cycle) is available for accessory service, eliminating the need for a recovery system (see Figure C-4).

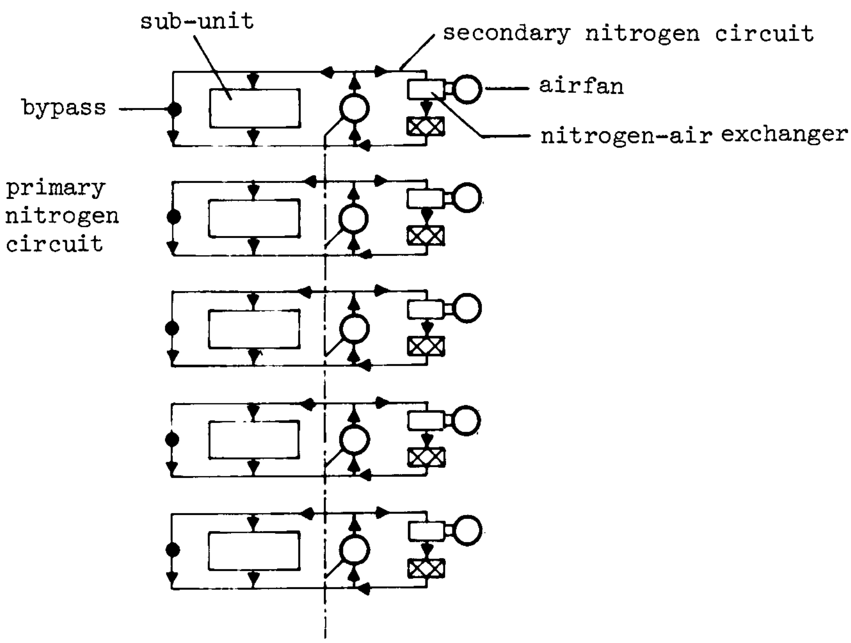

Figure C-4 - Schematic Diagram of Nitrogen Cooling and Preheating Systems (β"-Alumina type battery)

To start up the complete unit, it is heated by fuel oil burners (one burner per string, useful thermal power 2.5 MWth). The corresponding heat exchangers are located in the secondary nitrogen cooling circuit, whose temperature is raised to 400° C. The temperature difference in the primary nitrogen cooling circuit never exceeds 70° C. Start-up time from ambient temperature is approximately 17 hours. In the case of a total shut down without maintenance of nitrogen flow, the heat-up time required before start-up is as follows :

Shut-down time (days)	Heating time to start-up
3	immediate start-up
4	5 minutes
5	10 minutes + 5 minutes/subsequent day.
∞	17 hours is required for cold start-up

C - 10 STORAGE UNIT COST COMPARISON

The plant cost estimates for β- and β"-alumina are given in Tables C-22 and C-23.

Table C-22

Plant Cost Estimate

	β-Alumina	β"-Alumina
Yardwork	90,000	90,000
Civil and structural	190,000	185,000
Cost of planning and construction supervision (15 %)	42,000	41,000
Cooling and heating equipment	675,000	425,000
Control room equipment	150,000	150,000
Installation cost, equipment (10 %)	82,000	50,000
Installation cost, modules	210,000	210,000
Total ($)	1,439,000	1,151,000

Table C-23

Total Battery Cost ($ million)

	β-Alumina	β"-Alumina Nonoptimized	β"-Alumina Optimized
100 MWh modules factory cost	5.12	5.25	4.89
Taxes	0.84	0.88	0.80
After taxes return on investment	0.84	0.88	0.80
Battery selling price	6.80	7.01	6.49
Plant cost	1.44	1.15	1.15
Contingency on plan cost (20 %)	0.29	0.23	0.23
Marketing, Warranty, Miscellaneous cost	0.50	0.50	0.50
Total	9.03	8.89	8.37
$/kWh	90.3	88.9	83.7

C - 11 CONCLUSIONS AND REMARKS

Weight and cost parameters for β- and β"-alumina type of batteries are compared in Table C-24.

Table C-24

Final Comparison Between β and β"-Alumina

Cell weight parameters	β-Alumina kg	β-Alumina kg/kWh	β"-Alumina kg	β"-Alumina kg/kWh
Sulfur	0.691	1.693	1.072	2.050
Sodium	0.420	1.029	0.477	0.912
β-alumina	0.180	0.441	0.180	0.344
Steel container	0.303	0.743	0.356	0.681
Aluminum container	0.063	0.154	0.069	0.132
Carbon felt	0.057	0.140	0.089	0.170
Other	0.027	0.051	0.035	0.067
Total	1.735	4.252	2.278	4.356

Cell cost parameters	β-Alumina $	β-Alumina $/kWh	β"-Alumina $	β"-Alumina $/kWh
Alumina (material and labor)	6.040	14.80	6.512	12.45
Equipment depreciation on alumina	0.693	1.70	1.434	2.74
Rental costs on alumina	0.129	0.32	0.129	0.25
β-alumina factory cost	6.862	16.82	8.075	15.44
Sulfur	0.382	0.936	0.523	1.000
Sodium	1.034	2.534	1.163	2.224
Steel container	1.489	3.649	1.689	3.229
Aluminum container	0.336	0.824	0.367	0.702
Carbon felt	2.463	6.037	3.822	7.308
Thermo-compression	0.438	1.073	0.511	0.977
Quality control and tests	0.540	1.324	0.589	1.126
Other	0.702	1.720	0.816	1.560
Equipment depreciation on cell fabrication	0.57	1.40	0.73	1.40
Rental costs on cell fabrication	0.57	1.40	0.73	1.40
Cell factory cost	15.38	37.7	18.33	35.0

Table C-24

Final Comparison Between β and β"-Alumina (CONT'D)

Module weight parameters	β-Alumina kg	β-Alumina kg/kWh	β"-Alumina kg	β"-Alumina kg/kWh
Cells	250.0	5.0	237.0	5.17
Busbars	28.0	0.56	32.0	0.70
Concrete and other	228.0	4.56	210.0	4.58
Total	506.0	10.1	479.0	10.4

Module cost parameters	$	$/kWh	$	$/kWh
Cell factory cost	2,215.0	44.3	1,906.0	41.6
Busbar material and labor	116.0	2.3	126.0	2.7
Concrete	24.0	0.5	23.0	0.5
Assembly, control, other	87.0	1.7	71.0	1.5
Rental costs	78.0	1.6	71.0	1.5
Equipment depreciation	20.0	0.4	19.0	0.4
Module factory cost	2,540.0	50.8	2,220.0	48.4
Taxes and return	832.0	16.6	730.0	16.0
Module selling price	3,372.0	67.4	2,950.0	64.4

100-MWh unit	$ million	$/kWh	$ million	$/kWh
Battery selling price	6.80	68.0	6.49	64.9
Plant cost and contingency	1.73	17.3	1.38	13.8
Marketing, warranty,...	0.50	5.0	0.50	5.0
Total 100-MWh unit price	9.03	90.3	8.37	83.7

Following is a brief discussion of the relative advantages and disadvantages of using sodium-sulfur cells made with β"-alumina tubes.

C - 11.1 Disadvantages

- The factory cost of β"-alumina tubes is 8.4 % higher than that of β-alumina tubes, up from $6.54 to $7.09.

- When using β"-alumina the sulfur electrode must be made thicker for optimal performance and cost.

- It is absolutely necessary to assume the same production yield and the same reliability for β- and β"-alumina. Should we assume reduced reliability for β"-alumina, the necessary redundancy would be costly and the use of the β"-alumina would no longer be more economical.

C - 11.2 Advantages

- With appropriate optimization of the β"-alumina cell dimensions, the useful cell energy is increased by 28 %, from 408 Wh to 523 Wh. This more than compensates for the 19 % increase in cell price. The optimization consists of using a thicker electrode, and working with a lower electrode polarization especially during recharge.

- Obtaining 80 % efficiency instead of 75 % is less costly with β"-alumina than with β-alumina. In the case of β-alumina, the cheapest process is for a cell working at 75 % efficiency with the addition of a power recovery system to provide for electrical consumption of the accessories. However, in the case of β"-alumina, it is cheaper to make the cells work at 80 % efficiency and not use a power recovery system. This is an important simplification in plant design.

C - 12 FINAL RESULTS

The total cost of a 100-MWh unit with β-alumina type of cells (converter not included) is 90.3 \$/kWh. Substituting β"-alumina tubes for the β-alumina tubes without subsequent optimization reduces the cost by only 2 %, to 88.9 \$/kWh. Optimizing the β"-alumina cell by using a 40 % thicker cathode working in a smaller range (51 % instead of 63 % of the theoretical capacity) reduces the cost by 8 %, to 83.7\$/kWh. It must be reemphasized that these calculations assume that the reliability of β"-alumina will equal the reliability of β-alumina.

In sum, as far as large storage units are concerned, shifting from β- to β"-alumina does not produce as large a cost saving as anticipated. Technically, the use of β"-alumina indirectly permits several simplifications in the cathode requirements and in system design. In addition, anticipated improvements in cathode performances and lower cost for graphite material favor β"-alumina cells.

Part D

QUALITY CONTROL PROCEDURES

CONTENTS

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TABLE

QUALITY CONTROL PROCEDURES

This section discusses the quality control operations that take place when raw materials are received and at each production stage.

D - 1 RAW MATERIALS

The purity of raw materials is controlled through atomic absorption for K, Mg, and Si and through X-ray fluorescence for Ca and Fe. The upper limits of impurities allowed are given in Table D-1.

Table D-1
Allowable Limits Of Impurities
In The Raw Materials

Element	Upper limit (ppm)
K	10
Mg	20
Si	100
Ca	50
Fe	200

D - 2 BLENDING

Dry blending is accompanied by a slight milling. The specific area is measured by either the Blaine or the BET method. It is close to 1 m^2/g. The blending additive (organic compound) is chemically analyzed after calcinating in order to detect any traces of mineral products. The wear of the α-alumina milling medium is also checked and the ball load maintained as constant as possible by adding new balls after screening out the worn out balls.

D - 3 SYNTHESIS CALCINATION

The composition after the blend is fired is checked by X-ray diffraction. The synthesis of β- or β"-alumina leads to mixtures containing about the same amounts of β-alumina and β"-alumina. Traces of $NaAlO_2$ sodium aluminate may be present, but disappear at the sintering stage. The blend purity is also checked at this stage in order to make sure that no contamination occured during calcination.

D - 4 PREPARATION OF THE SLIP INTENDED FOR SPRAY DRYING

Slip density and viscosity are checked. The wear extent of the α-alumina milling medium is also checked and the ball load maintained as constant as possible by adding new balls after screening out the worn out balls.

D - 5 SPRAY-DRYING

D - 5.1 Powder intended for isostatic pressing

During spray-drying, the granule size distribution is checked by sieves. Also checked are :

- Volumetric index (1 sample every 100 kg)
- Moisture content, which must be as low as possible and according to which the spray-drying is adjusted
- Flow quality, as measured by slope angle

D - 5.2 Powder intended for electrophoresis

During spray-drying, the flow quality of the dried powder is controlled to ensure proper flow into the electrophoresis bath.

D - 6 FORMING

The geometric characteristics controlled after forming are : dimensions, wall thickness, and surface evenness after electrophoresis. The inside tube walls are checked visually for internal cracks or inclusions by lighting the tube from the inside. The specific gravity of the green tubes is also controlled and is expected to reach 2 g/cm^3.

D - 7 SINTERING

The inspections after sintering involve :

- Geometric characteristics and physical properties (diameter, length, thickness, ovalization, bowing, helium tightness, density, surface roughness, mechanical strength, diametral test, and burst strength)

- Phase identification by X-ray diffraction and Al/Na ratio by atomic absorption

- Detection of impurities (K, Mg, Si, Ca, Fe) by chemical analysis, atomic absorption, and mass spectrometry

- Electrochemical characteristics, mainly the resistivity value at 330° C (Na-S operating temperature) and the cycling behavior (transfer of a minimum amount of sodium)

D - 8 COST ESTIMATE

Following the Arthur D. Little recommendations, the cost of quality control has been included in the factory cost. Our estimates made allowance for inspection of each tube for geometric characteristics after shaping, appearance, helium tightness, burst strength, and geometric characteristics after sintering. Other characteristics, such as crystalline structure and microstructure, are statistically controlled. The costs resulting from these operations are included in the overhead.

Appendix 1

LABOR FOR CONTINUOUS SINTERING (M1)

The number of furnaces is set at 3,250 (§ A - 2.3.2). It is anticipated that a worker can load and unload 136 furnaces per shift. Inasmuch as each furnace is to be loaded or unloaded every 3 hours, the worker should be involved with loading/unloading every 80 s or so.

Assuming individual workers each work 220 shifts/year, full plant utilization will require 5 teams (to handle 365 days of 3 8-hour shifts). The number of workers required is thus 120.

$$\frac{3250 \text{ (furnaces)}}{136 \text{ (furnaces/man-shift)}} \times 5 \text{ shifts} = 120 \text{ workers}$$

10 supervisors are required (one supervisor/325 furnaces), so the total number of workers required for continuous sintering is : 120 workers + (10 supervisors x 5 shifts) = 170 workers. The labor for 100 tubes is :

$$\frac{170 \text{ workers} \times \dfrac{170 \text{ working h/mo}}{30 \text{ days/mo}}}{36364 \dfrac{\text{tubes}^*}{\text{day}} \times \dfrac{20 \text{ working days/mo}}{30 \text{ days/mo}}} \times 100 \text{ tubes} = 4.09 \text{ h}$$

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*assuming 20 working days/month